

EDDY COVARIANCE IN A TALLGRASS PRAIRIE: ENERGY BALANCE CLOSURE,
WATER AND CARBON BUDGETS, AND SHRUB EXPANSION

by

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Abstract

The exchange of water, carbon, and energy between grasslands and the atmosphere is an important biogeochemical pathway affecting ecosystem productivity and sustainability. The eddy covariance (EC) technique directly measures this mass and energy exchange. However, questions remain regarding the accuracy of EC-derived H_2O and CO_2 fluxes in landscapes with irregular topography and variable vegetation. These concerns stem from the “energy balance (EB) closure problem” (i.e., measured energy in does not equal measured energy out). My main objectives were to examine EB closure at two topographical positions within an annually burned tallgrass prairie watershed and to examine the effect of landscape position and woody encroachment on carbon and water exchanges. In tallgrass prairie, 14 km south of Manhattan, KS, USA, EC towers were deployed at three sites in 2007 and 2008. One upland and lowland tower were within an annually burned watershed dominated by C_4 grasses. Another lowland tower was deployed in a separate quadrennial-burned watershed where significant woody vegetation occupied the tower’s sampling area. All towers measured EB components (net radiation, R_n ; soil heat flux, G ; sensible heat flux, H ; and latent heat flux, λE). In the annually burned watershed, landscape position had little effect on G , H , and R_n with differences $\leq 2\%$ between sites. However lowland λE was 8% higher, owing to larger plant biomass/leaf area and greater soil moisture. Energy balance closure (i.e., $[\lambda E + H] / [R_n - G]$) was 0.87 and 0.90 at the upland and lowland sites, respectively. A nearby large aperture scintillometer provided good validation of EC-derived H in 2007. Data suggested that underestimates of λE may have accounted for the closure problem; sample calculations showed that increasing λE by 17 % would have resulted in near perfect closure. Data from this study suggests that EB closure does

not strongly correlate with topographical position; however these data raise questions regarding accuracy of the λE term. Mass exchange analysis shows that the prairie carbon cycle is highly dependent on burning. The lowland and upland annually burned sites saw carbon gains of 281 to 444 g C m⁻² yr⁻¹ *before burning* with the shrub lowland showing the least (e.g. 159 and 172 g C m⁻² yr⁻¹). After the prescribed burn, the upland and lowland sites remained slight carbon sinks (68 to 191 g C m⁻² yr⁻¹), whereas the unburned shrub site was a carbon sink in 2007 (159 g C m⁻² yr⁻¹, because no carbon loss was incurred via burning) and a large carbon source in 2008 when it was burned the following year (336 g C m⁻² yr⁻¹ loss). Evapotranspiration (ET) was highest at the shrub lowland where greater soil moisture and abundance of deep-rooted C₃ shrub vegetation allowed greater uptake and loss of water.

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Dedication

For those who taught me,
And sought out my best.
To all whose countenance
Motivated, guided, and comforted.
For you—the art of my work,
Which I present with pride.
For your dedication;
My sincere gratitude.

CHAPTER 1 - Introduction

The exchange of energy and mass between the surface and the atmosphere is a fundamental process that controls the environment in which we live. The complex nature of this transport is essential to understand, and such data presents countless opportunities for assessing ecosystem productivity, sustainability, or other important environmental topics. One such application that lends understanding of surface-to-atmosphere energy transfer is a micrometeorological technique called eddy covariance (EC). This technique allows for direct measurement of scalar and energy fluxes at the surface, and is the chief flux data collection method utilized by many continental-scale networks such as AmeriFlux, EuroFlux, Fluxnet Canada, OzFlux, AsiaFlux, and the planned National Ecological Observatory Network (e.g., Aubinet et al., 2000; Baldocchi et al., 2001; Field et al., 2006). Data from EC stations can be used to quantify annual carbon and water balances from an ecosystem on a watershed scale, and such data can be utilized for model parameterization (Kucharik et al., 2006), remote sensing (Turner et al., 2006) and ground-truth comparisons for regional models. Eddy covariance can be deployed for long periods of time to evaluate and predict annual ecosystem responses to land use change (e.g., consequences of converting native systems to agriculture, deforestation, woody encroachment, long-term effects of fire or grazing, desertification or anthropogenic influences). Such topics are incredibly relevant to building a foundation for the mutual well-being of the environment and its inhabitants.

Grasslands are particularly important ecosystems to study. Grasslands cover nearly half of the planet's land and 70% of all agricultural activity takes place within these vital biomes (FAO, 2009). Yet for their abundance, grasslands are often fragile landscapes that react quickly

to changes in land practices such as fire frequency, grazing, and alteration to intensive agriculture. In North America, the most dominant grassland ecosystem is that of the prairie which encompasses the majority of the Central Plains region from Mexico to Canada. The most productive type of prairie within this region is the tallgrass prairie, of which approximately 1% of the original extent remains (Pieper, 2005). The largest tracts of pristine tallgrass prairie occur in the Flint Hills region, occupying eastern Kansas and Oklahoma. Understanding the role grasslands (such as the tallgrass prairie) play in the global carbon and water cycle is very important. Utilizing EC within the tallgrass prairie allows measurement of the ecosystem's carbon storage and release, assessment of the implications of climate change, and how changes in land management and interannual variation can affect the carbon sequestration potential (Owensby et al., 2006; Suttie et al., 2005; Suyker et al., 2001). Eddy covariance has been successfully applied to tallgrass prairie for water, carbon, and energy balance assessments (Bremer and Ham, 1999, 2010; Ham and Knapp, 1998; Meyers, 2001; Owensby et al., 2006; Verma et al., 1992); and such research can be applied to grasslands worldwide. As climate change (i.e., sustainability) and productivity become growing concerns, the data provided by EC measurements will be increasingly important.

The tallgrass prairie of the Flint Hills contains an undulating terrain, consisting of uplands and lowlands. Typically, eddy covariance is deployed in flat upland landscapes where significant fetch (or sampling range) is thought to give more viability to the theory. However, increasing research has endeavored to apply EC to non-ideal topography (Baldocchi et al., 1988; Hammerle et al., 2007), with much success. Particularly within the tallgrass prairie, EC measurements in areas such as lowlands should uphold the fundamental theory behind the technique, as lowland areas are often level and similar in fetch to uplands. To accurately obtain

annual carbon and water fluxes for this ecosystem, one must consider both upland and lowland contributions.

As previously mentioned, grasslands like the prairie can be impacted by dramatic changes in land use. One of the most important processes affecting the composition and productivity of the prairie is fire. Historically, frequent prairie fires resulted from lightning strikes or the activities of indigenous peoples, but today fires are a controlled method of rejuvenating growth in the spring and eliminating detritus of the previous year. This helps to maintain a landscape relatively free of woody vegetation, as frequent fires kill or suppress plants with a longer growth cycle (e.g., trees, bushes) (Bremer and Ham, 1999; Suttie et al., 2005). If burning frequency were to lessen, woody plants gain more of a stronghold on the environment and once established, are hard to eradicate (Briggs et al., 2005). This has a major impact on tallgrass prairie in central North America, where extensive population growth in the 20th century coincided with increased crop production and fire suppression within the prairie domain. In the past few decades, research has highlighted the importance of prairie fires, and the practice has become more commonplace in the Flint Hills (Owensby et al., 1973), but many locations experienced heavy woody encroachment during prolonged lapses in fire control (Heisler et al., 2003; McKinley and Blair, 2008). Dramatic changes in the water, carbon, and energy budgets occur as a result of woody invasion, and this has important implications for the grassland ecosystems within the Flint Hills. In addition to quantifying the yearly carbon and water balances of tallgrass prairie for differing topographical positions, employing EC to examine the ecosystem responses to woody encroachment is also vital for gaining a comprehensive foundation of the biogeochemical processes that control the prairie ecosystem.

Though eddy covariance is extensively deployed and its measurements are incorporated for many uses throughout numerous disciplines, questions remain regarding the accuracy of the technique. This uncertainty stems from an issue coined by the micrometeorological community as “the energy balance closure problem”. Energy balance closure is obtained when the available energy, net radiation less sensible heat flux ($R_n - G$, estimated from meteorological data), is equal to the outgoing energy, the sum of sensible and latent heat fluxes ($H + \lambda E$, measured by EC). Wilson et al. (2002) showed that this problem persists throughout different ecosystems, climates, and regardless of instrumentation with an overall average energy balance closure of 0.8 for Fluxnet sites in the U.S. (i.e., the available energy, $R_n - G$, is underestimated by the outgoing energy, $H + \lambda E$, by 20%).

Because eddy covariance is employed globally to estimate scalar and energy budgets, much research has been conducted regarding the closure problem (Aubinet et al., 2000; Foken, 2008; Guo et al., 2009; Ham and Heilman, 2003; Kohsiek et al., 2007; Mauder et al., 2007a; Mauder et al., 2007b; Moderow et al., 2009; Oncley et al., 2007; Twine et al., 2000; Wilson et al., 2002). Foken (2008) wrote an overview paper examining the many findings and remaining questions surrounding the closure problem. He summarized three main factors that have been frequently postulated by the research community as contributing to the energy imbalance within a system: 1) errors resulting from measurement or post-processing procedures, 2) source areas for the turbulent fluxes ($H + \lambda E$) not coinciding with that of the available energy ($R_n - G$), and 3) energy fluctuations being missed due to advection or low frequency transport caused by landscape inhomogeneities.

It is, therefore, highly important to study energy balance closure within ecosystems such as tallgrass prairie. Doing so within highly homogenous tallgrass prairie should lend more

accuracy to measurements of EC because the theory is known to perform better in this domain (e.g., uniform landscape, little spatial variation in species composition, and higher regional wind speeds). It is apposite to apply the previously-stated strategies of utilizing EC in an upland and lowland position to an analysis of energy balance closure. This will result in a more representative examination of closure on a whole-watershed scale.

Objectives

The research presented in this thesis was conducted with two overarching goals in mind, both of which involve the implementation and examination of eddy covariance in a tallgrass prairie over a two-year study period.

- 1) To evaluate energy balance closure within the prairie ecosystem utilizing EC measurements:
 - a. deploy two instrumented towers on an annually burned watershed, one at an upland site and one at a lowland site, to assess the effect of landscape position on energy balance closure; and
 - b. match the source areas of all the energy balance component measurements to test closure without uncertainty regarding surface inhomogeneities between measurements of turbulent and available energy.
- 2) Assess the influence of topography and variable vegetation/burn regime on the carbon and water balances within the tallgrass prairie:
 - a. examine the differences in seasonal and annual CO_2 and H_2O exchange between upland and lowland EC sites within an annually burned watershed; and
 - b. compare EC measurements from an annually burned watershed to those from a lowland in a quadrennially-burned watershed influenced by the presence of significant woody vegetation (i.e., shrubs) within the sampling area.

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CHAPTER 2 - Energy balance closure at eddy covariance towers in tallgrass prairie

2.1. Introduction

Eddy covariance (EC) is an important micrometeorological technique utilized for studying the exchange of water, carbon and energy in the surface boundary layer (Baldocchi et al., 1988). This methodology is employed by continental-scale flux networks like AmeriFlux, Euroflux, OzFlux, AsiaFlux and Fluxnet Canada (e.g. Aubinet et al., 2000; Baldocchi et al., 2001). Eddy covariance provides non-invasive, continuous flux observations of different climates, terrains, and ecosystems. Data from flux networks has found widespread use for model verification/parameterization (Kucharik et al., 2006) and remote sensing (Turner et al., 2006). Additionally, management decisions are often administered at the field- or watershed-scale; eddy covariance can be used to compare the effects of land management (e.g., grazing, fire) on fluxes at comparable scales (Owensby et al., 2006). With its vast implementation, it is important that eddy covariance proves an accurate method for long-term flux measurements.

Current efforts are being made to better understand the nature of important biogeochemical processes, such as the water and carbon balances. Grasslands, in particular, are a major player in the carbon cycle. Nearly 70 percent of the planet's agricultural land is classified as grassland (FAO, 2009). With that in mind, assessing the role of grasslands in the global carbon cycle will yield more detailed and vital information regarding climate change, carbon storage/release, and land-use/sustainability practices within the scope of the world's grasslands (Owensby et al., 2006; Suttie et al., 2005; Suyker et al., 2001). The term "grassland"

encompasses many sub-biomes such as savannah, steppe, mesic, montane, and xeric shrublands; perhaps the most productive of these being the temperate grasslands including the North American prairie (Suttie et al., 2005). Particularly in tallgrass prairie, eddy covariance has often been used to study water, carbon, and energy balances (Bremer and Ham, 1999, 2010; Ham and Knapp, 1998; Meyers, 2001; Owensby et al., 2006; Verma et al., 1992). Clearly, measurements from the EC method must be as reliable as possible to accurately quantify the scalar and energy budgets within this valuable ecosystem.

Much research has been done to ascertain the viability of EC measurements through verification of fundamental processes, specifically the law of conservation of energy. This law is summed up in a particularly fitting aphorism by the Roman philosopher Lucretius (ca. 99 BC–ca. 55 BC): *De nihilo nihil*, or simply “Nothing comes from nothing.” For this to be true, the energy balance at the Earth’s surface must satisfy the following:

$$R_n - G = H + \lambda E + \Delta S \quad (1)$$

where R_n is net radiation, G is soil heat flux and heat storage in the soil, H is sensible heat flux, λE is the latent heat flux, and ΔS is the change in canopy storage, all in W m^{-2} . In uniform, shallow vegetation ΔS is characteristically small, thus the ratio of the system’s available energy, $R_n - G$ (meteorological data), to the outgoing energy, $H + \lambda E$ (measured by EC), should approximate unity—this is called energy balance closure.

However, most applications of eddy covariance do not achieve closure with a majority of energy balance studies reporting the ratio of $(H + \lambda E)/(R_n - G)$ to be about 0.80 (Wilson et al., 2002; Foken, 2008). This implies that either meteorological measurements of $R_n - G$ are

overestimated (i.e., R_n too large or G too small) or eddy covariance measurements of $H + \lambda E$ are underestimated, failing to fully account for the system's available energy. Because eddy covariance instruments measure CO_2 in the same way as λE , EC-derived carbon flux could also be in error (Barr et al., 2006; Goulden et al., 1996; Twine et al., 2000).

The “energy balance closure problem”, as it is known, has been studied extensively (Aubinet et al., 2000; Barr et al., 2006; Foken and Wichura, 1996; Foken et al., 2006; Foken, 2008; Goulden et al., 1996; Guo et al., 2009; Ham and Heilman, 2003; Hammerle et al., 2007; Heusinkveld et al., 2004; Hunt et al., 2002; Kanda et al., 2004; Kohsiek et al., 2007; Laubach and Teichmann, 1999; Massman & Lee, 2002; Mauder et al., 2007a; Mauder et al., 2007b; Moderow et al., 2009; Oncley et al., 2007; Twine et al., 2000; Wilson et al., 2002). Foken et al. (2006) details three factors with eddy covariance that may contribute to the closure problem: 1) measurement and post-processing errors, 2) errors resulting from the turbulent fluxes (H and λE) sampling different scales and source areas than R_n and G , and 3) errors resulting from advection and low frequency fluxes caused by heterogeneity of the land surface. A detailed discussion in an overview paper by Foken (2008) reasons the first factor to be resolved for most applications due to widespread agreement in established post-processing procedures. The second factor (often associated with the accuracy of radiation and storage measurements) is also shown by Foken (2008) and Kohsiek et al. (2007) to have a negligible affect on the lack of closure when great care is made to obtain accurate R_n and G measurements. A large emphasis is placed on spatial heterogeneity being the likely culprit.

The overview article also suggests the magnitude to which the low frequency portion of the third aspect is a concern can be determined through Ogive analyses (Foken and Wichura, 1996; Oncley et al., 1990), but for EC over short vegetation covering large regions (i.e.,

grasslands) sampling frequencies > 10 Hz with 30 minute integration allows for the capture of the majority of turbulent flux (see section 2.3.3). However, the effect of large scale heterogeneity across the landscape remains a proposed rationale for lack of closure in many systems (Guo et al., 2009; Kanda et al., 2004; Laubach and Teichmann, 1999).

Classic applications of eddy covariance locate net radiation and soil measurements in an area representative of but exterior to the main tower ¹*footprint*, or source area. Foken (2008) points out that this spatial mismatch in the $R_n - G$ and $H + \lambda E$ source areas has been a concern. He also cites the Energy Balance Experiment (EBEX-2000) by Mauder et al. (2007a) concerning $R_n - G$ measurements, where it was estimated that errors in these data are no more than 5% of the energy budget during daytime, not accounting for the 20% lack of closure. To confirm these observations, placing the measurements of R_n and G in the footprint of the EC tower would resolve if the spatial heterogeneity has any effect on closure, or if the scale mismatch is the main issue regarding eddy covariance and energy balance closure.

Additionally, collecting EC data at multiple locations across major topographical positions within a watershed will help to isolate whether closure can be achieved by considering spatial variations in the energy balance across the landscape. Moreover, interannual variability can play a large role in the degree of closure reported for long-term data acquisition. Specifically, is closure affected by the ratio between H and λE (i.e., the Bowen ratio), a parameter influenced by precipitation, soil water content, or plant water relations, etc?

The goal of this project was to evaluate the degree of energy balance closure across multiple years at two landscape positions in tallgrass prairie. With the objective of minimizing

¹ The surface region from which energy fluxes originate—the footprint directly affects measurements of available energy or turbulent efflux.

measurement and post-processing errors similar to other studies (e.g., EBEX-2000) in addition to examining the effect of spatial heterogeneity or sampling scale by collecting data at multiple locations across a watershed. Data were collected on pristine tallgrass prairie situated in Northeastern Kansas, USA where the windy summer environment combined with shorter, uniform vegetation provides sufficient turbulent mixing and an ideal location for EC measurements. Two EC towers were deployed on the same annually burned watershed one each at an upland and lowland landscape position during the summers of 2007 and 2008. Net radiation and G measurements were placed in the source area of each EC tower. Lowland locations demonstrate higher evapotranspiration and thus may have a higher λE component to the energy balance, a fact that may affect closure because the accuracy of the H_2O measurement becomes more important. Sensible heat flux output at each location was compared to that of a large-aperture scintillometer that continuously sampled a large transect south of both EC towers during the same time frame in 2007. This provided an important comparison for verifying H measurements. Additionally, net radiation and soil heat flux measurements were placed in the EC footprint, providing insight as to how energy balance closure was affected by combining the source area of available energy and that of the EC fluxes.

2.2. Methods and Materials

2.2.1. Site description

Research was performed at the Konza Prairie Biological Station (KPBS), approximately 14 km south of Manhattan, Kansas, USA (39.08 °N, 96.56 °W, 330 m). Data on turbulent fluxes were used from two eddy covariance (EC) stations that operated in the summers of 2007 and 2008. The EC stations were within the boundary of an annually springtime burned, ungrazed watershed. The sites were installed at different landscape positions; one on upland terrain (“Upland”, 441 m), and one at a lowland position (“Lowland”, 427 m) located approximately 350 m south of the upland site (Fig. 2.1). The source area for the upland tower included very level, uniform terrain. The lowland site was on a gently sloping footslope near the bottom of the catchment that drained the watershed. Both sites had highly uniform vegetation dominated by warm-season, perennial C₄ grasses including *Andropogon gerardii* (big bluestem), *A. scoparius* (little bluestem), *Sorghastrum nutans* (indiangrass), and *Panicum virgatum* (switchgrass) (Gibson and Hulbert, 1987). Annually burned watersheds showed on average 384 and 581 g m⁻² aboveground biomass for uplands and lowlands, respectively, over a 16-year study (Heisler and Knapp, 2008). Historical surveys demonstrate that lowland sites possess deeper soils with greater water-holding capacity than uplands (Briggs and Knapp, 1995). Soils at each EC station are silty clay loams (Benfield series: fine, mixed, mesic Udic Argiustolls) (Bremer and Ham, 1999). The 30-year average annual precipitation for all sites is 859 mm. Additional background information on tower measurements in the watershed can be found in Ham and Knapp (1998) and Bremer and Ham (1999).

2.2.2. Instrumentation and sampling

Eddy covariance stations were composed of a main tower supporting the core eddy covariance measurements of sensible heat, latent heat and CO₂ fluxes, and an ancillary/meteorological instrumentation site to sample available energy ($R_n - G$). EC instruments were mounted at 3 m on each main tower and consisted of an open-path infrared gas analyzer (LI-7500, Licor, Inc., Lincoln, NE), a sonic anemometer (CSAT3, Campbell Scientific, Inc., Logan, UT), and a temperature/relative humidity probe (HMP45C, Campbell Sci.). Sensor separation between the CSAT3 and the LI-7500 was 0.14 m, CSAT3 orientation was 210° magnetic, and the LI-7500 was rotated 15 degrees vertically towards the footprint to obtain the least obstruction of flow by sensor body on the infrared beam and also to allow water to run off the lens. Eddy covariance data were logged at 20 Hz using a CR1000 data logger (Campbell Sci.) and collected via Compact Flash card at each site. All other meteorological data were sampled at 10 s intervals, and averages of these data were computed and logged every 30 minutes. In-situ calibration was performed to zero and span the CO₂ and H₂O measurements from the LI-7500 every two weeks using tank gas and a LI-610 portable dewpoint generator (Licor, Inc.)

Net radiation and G were measured in the footprint of each tower. A CNR2 net radiometer (Kipp and Zonen, Delft, The Netherlands) was deployed at 2 m near the center of each tower's source area approximately 30 m south of the EC instruments (i.e., along the prevailing wind). Soil heat flux was determined via the combination method (Fuchs and Tanner, 1968; Kimball and Jackson, 1979) and these measurements were also placed 30 m south of the EC tower (near the CNR2 measurements) with a replication installed 3 m south of the tower. Soil instrumentation at each replication included: two soil heat flux plates at 7 cm depth (HFT3,

REBS); soil moisture sensors at 3.5 cm (ML2x Theta Probe , Delta-T Devices, Cambridge, UK); and type-E soil thermocouples at 2 and 5 cm (TCAV, Campbell Sci.). Soil heat flux at the surface was approximated as the sum of heat flux at the depth of the plates (7 cm) and the rate change in heat storage in the 0 to 7 cm layer above the plates. Soil heat capacity needed for the heat storage term was computed from soil water content and soil bulk density (1.0 g cm^{-3} , from field samples) using the equation of deVries (1963). Meteorological data were logged with Campbell Scientific CR23X data loggers and AM16/32 Multiplexers.

Longwave radiation as measured by the pyrgeometer on the CNR2 net radiometer was calibrated in the laboratory using a longwave source (personal communication, J.L. Heilman, Texas A&M University, College Station, TX). The calibration of the up- and down-facing pyranometers on the CNR2 radiometers was checked against an Eppley PSP Pyranometer, (The Eppley Lab, Inc., Newport, RI). Factory calibration of the pyranometers proved accurate against the Eppley PSP; however, longwave measurements from the pyrgeometers needed adjustment by +40.9 and + 34.1% from factory calibration at the upland and lowland CNR2s, respectively. The calibrated CNR2s were also compared to a CNR1 (4-component Kipp and Zonen radiometer) and found to be in excellent agreement.

Soil moisture probes were site-calibrated against gravimetric soil samples taken near the location of each set of probes across varying moisture contents throughout the summer and compared with lab output as per recommended calibration procedures. Field data for biomass and leaf area index were collected manually at early-, peak-, and late-growth stages at both sites (Table 2.1). Each biomass harvest consisted of clipping four 0.25 m^2 samples at 15 m intervals each from an east and west transect around the main tower footprint (eight samples total per site). Early and peak samples were analyzed for photosynthetic leaf area index using a LI-3100C

Area Meter (Licor, Inc.) and weighed post-drying to obtain biomass estimates representative of the footprint for each main tower.

In 2007, a large-aperture scintillometer (LAS; Kipp and Zonen) was utilized to collect path-averaged turbulence data along a 500 m horizontal transect south of both EC stations. The transmitter and receiver were situated on upland terrain in the study watershed and adjacent watershed. The measurement transect spanned a large region of the watershed upwind of the tower sites (when wind direction was from the prevailing southerly direction) (Fig. 2.1). The LAS was accompanied by a weather station which took measurements of R_n and G at an upland position using a CNR1 radiometer (Kipp and Zonen) and soil heat flux instruments. Details on the LAS system and methods of calculations are provided in Brunsell et al. (2008). The LAS measurements of H were compared to those from the upland and lowland EC tower.

2.2.3. Data processing

Post-processing of the EC data closely followed the procedures outlined in Baum et al. (2008). This included utilizing the EdiRe software package (version 1.4.3.1167, R. Clement, University of Edinburgh, UK) to correct EC data for despiking, lag removal, planar fit coordinate rotation (Lee et al., 2004; Wilczak et al., 2001), frequency response corrections (Massman, 2000; Moore, 1986), sonic-temperature sensible heat flux corrections for humidity (Schotanus et al., 1983), and density corrections on CO_2 and H_2O measurements (Webb et al., 1980).

Corrected data were filtered to include only dominant southerly wind directions, $u^* > 0.15$ to ensure sufficient turbulent mixing, and $R_n > 125 \text{ W m}^{-2}$ to correspond with maximized fluxes of R_n , G , H and λE . Filtered fluxes were used to compute energy balance closure. See section 2.3.2. for additional information on filtering criteria.

2.3. Results and Discussion

2.3.1. *Interannual environmental conditions and biomass*

Calculations of energy balance closure were based on data from 21 Jun to 30 Sep (Day of Year, DOY, 172 – 273) for both 2007 and 2008. This timeframe encompasses the most productive portion of the growing season in tallgrass prairie, and therefore reflects maximized fluxes of λE and R_n . In 2007, growing season precipitation between 1 May and 30 Sep was 496 mm; below the historical average by 21 mm. However, 67% of this rainfall occurred in the first two months, with almost half of the total precipitation occurring in May alone (45%, Fig. 2.2). The study started on 21 Jun, during a relatively wet part of the 2007 season, with average volumetric soil moisture values at the upland and lowland at field capacity ($\sim 0.40 \text{ cm}^3 \text{ cm}^{-3}$). Air temperatures for 2007 (as observed in Manhattan, KS, 14 km north) were only 0.2°C below average 1 Jun – 31 Jul, but the remainder of the summer from 1 Aug – 30 Sep, daily air temperatures exceeded the historical mean by 2.1°C on average (Weather Data Library, Kansas State Univ.). During the more heat-stressed portion of the summer in Aug and Sep, two significant drydown periods occurred; DOY 180 to 203 and 216 to 232. The water demand was quite substantial during the latter part of the summer in 2007. Reference-crop evapotranspiration (ET) (Allen et al., 1998) from DOY 172 to 273 exceeded precipitation by 278 mm (Table 2.2), calculated from daily T_{max} , T_{min} , relative humidity (RH_{avg}), average windspeed, and total R_n from the upland and lowland sites, respectively.

Contrastingly, 2008 was a much wetter year (total precipitation was 747 mm, 230 mm above average for 1 May – 30 Sep). Precipitation events occurred at nearly-even intervals with monthly rainfall totals and soil moisture remaining consistent over the summer. This is atypical

behavior because precipitation events tend to be intense and sporadic for this region. In addition, air temperatures were lower than average by 1.2 °C. On the initial date from which data were collected for comparison with 2007 observations, volumetric soil moisture paralleled 2007 data—around 0.40 cm³ cm⁻³, at each site. In 2008, the environment experienced little stress regarding water supply and heat as precipitation exceeded reference crop ET by 113 mm (Table 2.2). This resulted in an exceptionally large biomass production in comparison with 2007 (Table 2.1). Heisler and Knapp (2008) used similar techniques for biomass collection and compiled peak biomass data for KPBS ungrazed annually-burned watersheds, of which the 16-yr average for upland and lowland positions was 384 and 581 g m⁻², respectively. Aboveground biomass harvests in this study exceeded the 16-yr average at the upland and lowland EC sites by 26 and 2% in 2007 and by 40 and 33% in 2008, respectively.

2.3.2. Landscape position effects

All fluxes were filtered with respect to wind direction (θ), friction velocity (u^*), and daytime net radiation. Isolating the data most representative of the EC footprint during the diurnal efflux peak yields maximum fluxes with which to determine closure. Data were included for closure computation if the corresponding filter parameters met the following criteria: prevailing southerly wind directions ($165^\circ < \theta < 255^\circ$), sufficient turbulent mixing ($u^* > 0.15$) (Barr et al., 2006; Goulden et al., 1996), and daytime radiation ($R_n > 125 \text{ W m}^{-2}$). In this paper, the term “full filter” is defined by the latter statement. Datasets also were analyzed with wind direction and u^* filters only (“wind filter”) and additionally with no filtering (“unfiltered”).

2.3.2.1 Energy balance components

Composite diurnal trends were compiled from unfiltered data of H , λE , R_n and G for three periods of equal length throughout the summers of 2007 (Fig. 2.3) and 2008 (Fig. 2.4) at the upland and lowland sites. Each 34-day-long period corresponds to one-third of the timeframe for collection commencing on the summer solstice and concluding at the end of Sep. The energy balance of the tallgrass prairie ecosystem is largely driven by R_n and λE during the summer. Obtaining accurate measurements of λE is very important for determining the degree of closure within this system. Latent heat flux was the dominant form of energy loss in early 2007, but even more so in 2008 when water was not limiting (Table 2.3a). On average, λE fluxes were about 8% greater at the lowland site for both years (Table 2.3b), which one would expect as a result of the higher water availability and leaf area at the lowland site. This is demonstrated well by looking at data from 2007. As the environment became more arid in late 2007, the lowland experienced less stress than the upland. During this timeframe, the largest difference between upland and lowland λE for the entire study was seen (14.5%, Table 2.3a). For the most part, this trend is noted for both summers (even considering the wetness of 2008). Sensible heat flux varied little between sites, despite the differences across the landscape, and as expected H increased after the canopy reached its peak and began senescence in the late summer. Fluxes of H and λE will be discussed more in section 3.4.

Throughout both summers soil heat flux deviated marginally in magnitude and between sites (Table 2.3a and b). Because these data span the most productive part of the growing season where the canopy largely controls the energy exchange to the surface, storage or release of heat in the soil remains small. During FIFE (the First International Satellite Land Surface

Climatology Project [ISLSCP] Field Experiment), conducted on the Konza prairie in 1987 and 1989, measurements of soil heat flux showed agreement with our observations in Figs. 2.3 and 2.4, where G differed little between uplands and lowlands (daytime maximum of $\sim 10 \text{ W m}^{-2}$ higher at uplands during the growing season; Smith et al., [1992]).

Net radiation was similar between the two sites (i.e., within 2.1 % on average). Any discrepancies are likely due to differences in surface albedo and possibly patchy cumuliiform cloud cover (Smith et al., 1992). The maximum deviation between sites for net radiation occurred mid-summer 2007 where the upland site had $1.0 \text{ MJ m}^{-2} \text{ d}^{-1}$ more integrated R_n than the lowland site (Table 2.3a). The minimum difference was for 21 Jun – 24 Jul, 2008 where the average daily accumulation of net radiation was equivalent at both sites. Overall, averages for each year show that the upland received more net radiation per day by 0.5 and 0.2 $\text{MJ m}^{-2} \text{ d}^{-1}$ in 2007 and 2008, respectively. This disagrees with the trend noted by Smith et al. (1992) between hilltops and bottoms, however, it is important to stress that these differences are very small ($\sim 2\%$ for both years, Table 2.3b) where they were also marginal in said paper.

Despite the homogeneity of the study watershed, noted differences exist between prairie uplands and lowlands that are consistent throughout the Flint Hills: (1) upland locations typically experience higher wind speeds, (2) lowlands see increased drainage and have a deeper soil layer which allows for better retention of moisture, thus (3) higher biomass production is generally observed within watershed bottoms. Considering these observations, one might have expected larger variations in the energy budget than was observed. Data suggest that topography-induced differences in soil water within a catchment do create differences in λE in the range of 5 to 13% between uplands and lowlands. Otherwise the deviation across the landscape was quite small, at least with the precipitation levels of 2007 and 2008. Of all the variables discussed, the largest

difference between the two sites is that λE accounted for more of the net radiation flux at the lowland position (Table 2.3a and b), which is consistent with greater soil water holding capacity usually seen in these topographical regions.

2.3.2.2 Regression comparison of incoming and outgoing energy

The energy balance closure coefficient, α , represents the portion of available energy that is fulfilled by the sensible and latent heat fluxes,

$$(R_n - G) = \alpha (H + \lambda E) + b \quad (2)$$

where b is the intercept, or offset, of the regression analysis between incoming and outgoing energy and α is the slope. Coefficient and intercept estimates result from an ordinary least-squares (OLS) linear fit for plots of full filter data (i.e., R_n and wind filters) during the same three consecutive periods previously discussed (Figs. 2.5 and 2.6). In the early summer of 2007, values of α at the upland and lowland were 0.786 and 0.790, respectively. Mid- to late-summer closure coefficients tended to increase as the prairie system became increasingly water- and heat-stressed in 2007 (Fig. 2.5). In late Jul through Aug, $\alpha = 0.835$ at the upland, and the lowland displayed $\alpha = 0.864$. The end of the summer (28 Aug – 30 Sep) displayed little deviation in α , though for this period the order was reversed where $\alpha_{up} < \alpha_{low}$ by 2.9% during 25 Jul – 27 Aug, but $\alpha_{up} > \alpha_{low}$ by 1.5% for the last third of the summer ($\alpha = 0.846$ and 0.831 for 28 Aug – 30 Sep, upland and lowland, respectively). For the most part, α leveled off after increasing mid-summer as the environment became gradually more desiccated from the heat and a strong precipitation deficit. The summer of 2007 did not, however, demonstrate a marked difference in

lack of closure between upland and lowland—each averaging a closure coefficient of 0.822 (upland) and 0.828 (lowland) with an average intercept of 13.3 and 15.2 W m⁻² (upland and lowland) for the entire summer.

The lowland site displayed slightly greater α than the upland in 2008 on average, but both sites had higher offsets for most of the timeframes in 2008 over those seen in 2007 (Fig. 2.6). Upland coefficients were 0.755, 0.857, and 0.834 for the first, second, and third periods in 2008, respectively. The energy balance coefficient was larger in 2008 at the lowland for the first period (0.848), converged with upland α for the second time period (0.854), and exceeded the upland site for the third period (0.869). Average offsets for the 2008 regression plots were 15.3 and 29.7 W m⁻² at the upland and lowland, in that order. The larger intercept values in 2008 indicate a positive bias in the data, but to reiterate, differences between years in b are small.

On average, $\alpha_{\text{up}} = 0.822$ and 0.815 while $\alpha_{\text{low}} = 0.828$ and 0.857 in 2007 and 2008, respectively. Both years the mean upland intercept was 14.7 W m⁻² while the lowland showed intercepts averaging 22.5 W m⁻². Variation in α_{up} was -0.7 % from 2007 to 2008 and α_{low} was +2.9% higher in 2008 than 2007. The average offset changed by +2.9 W m⁻² in 2008 from 2007 at the upland site, and the lowland site offset increased by 14.4 W m⁻² from first to second year. In comparing the two summers, regression analysis of our data suggests that EC performed in a lowland position within tallgrass prairie has a marginally higher degree of closure than EC at an upland location occupying the same watershed. Average closure coefficients for upland and lowland amounted to 0.819 and 0.843 across both summers, respectively. The topographical differences in α and the intercept are not large ($\alpha = 83.1 \pm 3.5\%$, offset = 18.6 ± 10.7 W m⁻² for the entire watershed).

Similar findings were reported by Hammerle et al. (2007) over meadows in Austria where EC data were tested for closure using measurements from two different elevations along a mountain slope. They saw that turbulent surface fluxes averaged 71 and 72% of the available energy for the two locations (high and low elevations, respectively). The variation in closure between the two sites is nominally smaller than what was observed at the Konza Prairie, especially considering the drastic elevation difference of 800 m versus the difference of 14 m between our upland and lowland sites. Though the study in Austria partitioned EC data into growing season intervals (as we did in our study), closure data was not presented on a periodic basis so seasonal drift in closure could not be compared to our results.

A tussock grassland in New Zealand studied by Hunt et al. (2002) using the EC method was found to have good closure over the summer (0.87 – 1.03). The tussock grassland system does not, however, depend on λE as a strong driver of the daytime energy budget like in the tallgrass prairie where productive grasses result in maximal values of ET upwards of 8 mm d⁻¹ (seen early Aug 2008 at the lowland site, data not shown) in contrast to the maximum evaporation rate of 3.8 mm d⁻¹ from the short tussock grassland seen in the aforementioned study. Of the three days analyzed for closure by Hunt et al., (2002), λE values decreased from 5.1 to 1.0 MJ m⁻² d⁻¹, while H increased dramatically from 4 to 9.8 MJ m⁻² d⁻¹.

In 2002, Ham and Heilman (2003) conducted EC in a cedar forest near Manhattan, KS and additionally from the same upland location as in this study on the Konza Prairie. Closure coefficients in Jun were 0.96 at the forest where fluxes of H were much higher comparatively than at the prairie. For the same period at the prairie, $\alpha = 0.79$ (regression data adjusted to a zero-intercept for both sites). Concentrating on the prairie data, the findings by Ham and Heilman (2003) are very similar to those from Figs. 2.5 and 2.6. Results from 2002 and 2007 –

2008 for the upland site show no obvious difference in closure despite the year-to-year variation (e.g., severe drought in early summer 2002 compared to 2007 and 2008 where there was little-to-no precipitation deficit in the early growing season).

The linear fit for each plot in Figs. 2.5 and 2.6 had little scatter as data was processed using all three filtering criteria (R_n , u^* and θ). Coefficients of determination (R^2) indicated good correlation between incoming and outgoing energy both years, ranging from 0.846 to 0.946.

2.3.2.3 Residual surface energy

When the energy balance cannot be closed, equation 1 can be modified to quantify any leftover energy, referred to as the energy balance residual. Calculations of residual energy were made by solving eq. 1 inferring lack of closure,

$$E_{\text{res}} = R_n - G - H - \lambda E \quad (3)$$

where E_{res} is measured in W m^{-2} . As the fluxes of the various terms from the energy balance increase, the energy residuum increases, as well. This energy has a distinct diurnal trend that did not vary much throughout the study period (Fig. 2.7). Seasonal composites of average half-hourly residual energy show a maximum during midday, demonstrating strong correlation with patterns of λE and R_n (Figs. 2.3 and 2.4). Both sites in 2007 showed agreement with maximal residuals of approximately 89 W m^{-2} , but in 2008 the sites differed more near solar noon where upland E_{res} peaked around 98 W m^{-2} and E_{res} at the lowland was 70 W m^{-2} . Residual values became negative during the night and tended to be similar between sites. The energy deficit only approaches zero at dawn and dusk. The integrated daily residual from Fig. 2.7 is the same for

both years at the upland ($1.4 \text{ MJ m}^{-2} \text{ d}^{-1}$), while the lowland site accrued 1.1 and $0.7 \text{ MJ m}^{-2} \text{ d}^{-1}$ for 2007 and 2008, respectively. Accumulated daily residuals here are positive (i.e., turbulent fluxes underestimate available energy in the system).

It is commonplace among researchers evaluating EC for closure that the energy imbalance manifests as a deficit of the available energy. In east-central Germany, Laubach and Teichmann (1999) paid special attention to inhomogeneities within the EC flux footprint, and they noted the propensity for underestimation of available energy in flux data over a mixed-grass site (α ranging $0.76 - 1.07$, with small negative intercepts). Each value for closure was determined from varying sensor heights on the EC tower (to change the source area) over two consecutive summers. On average, their closure coefficients were good the first year (0.89) and very good the second (0.97), but the underestimation was still evident. Consideration of sensor uncertainty and addition of photosynthetic heat flux computation did not explain the energy residuum alone, which approached nearly 100 W m^{-2} during daylight (Laubach and Teichmann, 1999). It also was mentioned that the components of available energy were not representative of the entire study area because much of the footprint varied in canopy height and species composition, but this effect on closure was deemed negligible. They discussed that detailed source area analysis could resolve the variability in closure based on seasonality and wind direction, but studying heterogeneities does not reveal them as the reason for lack of closure, and in particular, why turbulent fluxes typically underestimate available energy. The paper concluded that similarity theory-based applications (i.e., EC) are only apposite over impeccably homogeneous landscapes, which in actuality is unrealistic. Such findings can give weight to EC performed in landscapes that are decently homogeneous and flat, where basic theoretical assumptions regarding the application of EC are more likely to lend validity to corresponding

measurements. Despite this assertion, which has been generally agreed upon in the scientific community, ideal locations for EC continually turn up energy imbalances as well (Oncley et al., 2007; Paw U et al., 2000; Wilson et al., 2002).

It is to be noted that our filter criteria vary from that of other studies. Our objective was to isolate data from the upland and lowland tower that would be the most accurate for each energy balance component, and also to narrow down a dataset that corresponds to daytime hours when the residual is generally highest (see section 2.3.2). Most studies filter for prevailing wind speed (after post-processing) and a few filter for friction velocity.

2.3.3 Concomitant source-areas and low frequency fluctuations

To date, extensive work has been done to determine the accuracy with which available energy can be measured, particularly in regard to estimates of net radiation (Kohsiek et al., 2007; Laubach and Teichmann, 1999; Moderow et al., 2009; Schmid, 1997; Twine et al., 2000). This is important to establish as net radiation is usually the dominant energy input into terrestrial ecological systems. Generally, radiation measurements exact the most precise data while sampling the energy balance (Kohsiek et al., 2007; Twine et al., 2000), but despite the dependability of the instrument, landscape heterogeneities that may exist between the field of view of the radiometer(s) and the EC footprint have often been considered a possible contributor to the overall energy imbalance (Foken et al., 2006; Foken, 2008; Laubach and Teichmann, 1999; Schmid, 1997; Twine et al., 2000; Wilson et al., 2002).

Perhaps the most advisable paradigm is to compute net radiation as the sum of the incoming and outgoing longwave and shortwave components (Halldin, 2004; Kohsiek et al., 2007). In this study, the CNR2 (Kipp & Zonen) was utilized, which is a radiometer that

measures net radiation from the four components. These measurements were placed 30 m into the prevailing direction of the EC footprint to match the source area of the radiation measurements with the EC source area. At the same time, a Q*7.1 net radiometer (REBS, Inc.) was positioned in a more traditional deployment in a chosen representative area approximately 10 m external to the EC footprint. Comparisons between the CNR2 and the Q*7.1 match observations made during EBEX-2000 between a CNR1 (a highly regarded model similar to the CNR2, also a Kipp & Zonen) and the Q*7.1 (Kohsiek et al., 2007) (data not shown). Recall from section 2.2.2 that CNR2 measurements of short- and long-wave radiation in the prairie had excellent agreement with data from a CNR1 running simultaneously within an adjacent watershed. Based on these results, the CNR2 was determined the more accurate measure of net radiation at the two EC sites and thus was used solely for radiation measurements within the EC source area (and thus, the only R_n data utilized for energy balance calculations). In addition to employing measurement of R_n by the four components, incorporating these measurements from within the footprint adequately tests the R_n -part of the second factor mentioned by Foken et al. (2006) regarding mismatched source areas, and produces a high quality dataset of net radiation for this study.

Soil heat flux calculations were an average of two separate soil instrumentation suites. The first grouping of instruments was positioned in the vicinity of the CNR2 net radiometer within the EC footprint. A replication of the soil instrumentation was also installed 3 m south of the tower in a more traditional deployment configuration (i.e., along the prevailing wind). Figure 2.8 shows the average difference between the traditional deployment and the footprint soil measurements. Some spatial variability exists between the two installments, but these are still small in regards to the available energy. The largest average diurnal deviations in G between the

tower and footprint deployments ranged $\pm 15 \text{ W m}^{-2}$ at the upland, and G at the lowland varied by about $\pm 8 \text{ W m}^{-2}$. Smith et al. (1992) showed for annually burned, ungrazed watersheds (similar to this study) that available energy within the Konza prairie tended to depend more on the magnitude of incoming net radiation than on variations in soil heat flux. By utilizing the mean soil heat flux of the location near the tower and the position within the EC prevailing sampling area, a more representative estimation of soil heat flux was obtained for determining closure.

Although our data did not reveal the recondite nature of the systematic energy imbalance using EC, improvements had been made in regards to maximizing closure within this study's watershed. As stated previously, Ham and Heilman (2003) reported a closure coefficient of 0.79 at the same upland site on KPBS, while the current study estimated closure across two years for the upland to be around 0.82. Given the high quality dataset of available energy, it appears that possible spatial variation between traditional R_n and G source areas and the EC footprint has little effect on overall closure within the tallgrass ecosystem, let alone accounting for the 20% energy deficit.

Many studies have considered the contribution of low frequency fluctuations when assessing this systematic 20% energy imbalance (Foken and Wichura, 1996; Oncley et al., 1990). To evaluate whether the tallgrass prairie environment elicits energy exchanges at lower frequencies, Ogive analysis is performed to test if the sampling frequency and averaging interval of EC data adequately captures these exchanges (Foken and Wichura, 1996). Eddy covariance data in this study were collected at 20 Hz with integration periods of 30 minutes. Based on Ogive analysis, there was no evidence that pointed to loss of flux through low frequency transport (data not shown). Results from this analysis also suggest that averaging intervals of 20

minutes would be acceptable. Half-hourly fluxes are more than sufficient to describe H and λE in this system.

2.3.4 Latent and sensible heat flux and energy balance closure

Fluxes of latent and sensible heat are often used to quantify the evaporative demand of an environment by evaluating the ratio of $H / \lambda E$, which is called the Bowen ratio (BR). Typically, $BR < 1$ indicates a more mesic environment, whereas $BR > 1$ points to an arid environment. In northeastern Kansas, BR usually increases throughout the latter portion of the growing season when precipitation input tends to slow in correspondence with seasonal temperature maxima. As the summer progressed in 2007 and 2008, closure seems to improve (Fig. 2.9). This development corresponded with increasing BR as the environment tended to dry, but correlation between closure and BR is low for both years ($R^2 = 0.196$, not shown). Other studies have found no discernible correlation between closure and BR (Moderow et al., 2009; Wilson et al., 2002). However, despite lack of regression correlation, many studies have obtained excellent closure in environments with high BR's (Ham and Heilman, 2003; Heusinkveld et al., 2004; Hunt et al., 2002; Mauder et al., 2007b). Visual assessment of increased closure over time is more apparent in 2007 when a late season dry spell portended higher BR's than in 2008. Any correlation by eye could be an artifact of less R_n and λE (i.e., less overall energy) in the environment during late summer, both of which dominate the energy exchange of the prairie system.

Due to the strong influence of R_n on the energy budget, daily average energy balance closure was computed as a function of R_n :

$$\text{Closure (\%)} = 100 \times (H + \lambda E + G) / R_n \quad (4)$$

which was the equation used to compile Fig. 2.9 and Table 2.4. In 2007, closure averaged 86.5 and 87.5% at the upland and lowland, respectively (87.0% overall, Table 2.4). The degree of closure varied more in 2008 where higher λE fluxes at the lowland may have contributed slightly more outgoing energy to the overall budget. The lowland site estimated the energy balance at 93.6% of the available energy, while upland closure was 85.8% with a watershed average of 89.7% (Table 2.4).

The 2007 study period coincided with the deployment of a large aperture scintillometer (LAS) that spanned a 500 m transect south of both EC towers (Fig. 2.1). Integrated fluxes of sensible heat were recorded along the 500 m long optical path and processed via the methods of Brunsell et al., (2008). LAS sensible heat flux data was compared to that of both towers (Fig. 2.10a). Sensible heat flux derived from the LAS (H_{LAS}) was marginally greater than lowland H and slightly less than H measured at the upland. Considering the differences in scales and techniques, the agreement is good. There is no clear evidence that H is being underestimated by the EC instruments.

When the latent heat flux is computed as a residual of the energy balance using H_{LAS} , the resulting λE_{LAS} is always larger than the EC fluxes of λE (Fig. 2.10b). However, this is because closure is forced as a result of using the λE residual. If closure were to be forced for the EC systems in the same way, λE would have to be computed as a residual of the energy balance:

$$\lambda E_{res} = R_n - H - G \quad (5)$$

where $\lambda E_{\text{res}} > \lambda E$ for most applications. This latent heat residual can be utilized to find the proportion of residual energy that can be accounted for by increasing λE estimates by some kind of correction factor.

The latent heat correction coefficient, $c_{\lambda E}$, is computed from the full filter data that comprises Fig. 2.9 and Table 2.4. The summer mean of each variable (R_n , H , and G) is used to find the average λE_{res} , from which $c_{\lambda E}$ is calculated as

$$c_{\lambda E} = \lambda E_{\text{res}} / \lambda E \quad (6)$$

which for both sites and both years yields a value of $c_{\lambda E} = 1.17$. By using corrected values of λE in the same closure computations shown in Table 2.4, upland closure changes from 86.5 to 96.8% and 85.8 to 98.9% in 2007 and 2008. Lowland closures increase to 98.7 and 107.1% from 87.5 and 93.6% in 2007 and 2008, respectively. This means that if λE were merely corrected by 17%, the watershed-scale energy budget would be closed by 97.8 and 100.3% for the two consecutive years in this study (whole-watershed average closure estimated from λE_{res}).

For completeness, H was also computed as a residual of the energy balance in the same way λE was (see eq. 5, exchange λE terms with H). Using the same procedure to find a sensible heat flux correction coefficient, we calculated $c_H = 1.96$. Overall yearly closure for the entire watershed increases to 105.5 and 99.1% using the corrected H . Although estimating H_{res} this way essentially closes the energy balance, this approach seems unrealistic as H would have to be doubled to account for the energy residual. In a prairie ecosystem like that of the Konza prairie, λE is the major form of heat loss from the environment during the growing season (especially during daytime when E_{res} peaks). If an underestimation of λE is occurring, but this dataset

shows no obvious indication of H being in error by nearly 96%, then it brings to question the accuracy of the λE term itself. A 17% error in latent heat flux across two years for an entire watershed could translate into a disconcerting underestimation of the yearly carbon balance. This is especially true for the watershed in this study where nuances in the estimation of carbon storage can classify the prairie as either a source or a sink after carbon loss from annual biomass conflagration is included in the overall yearly carbon budget.

2.4. Conclusion

Much discussion has taken place over what the “ideal” landscape is in which to perform eddy covariance (EC) measurements. Many would agree that tallgrass prairie can provide the ingredients known to make EC more viable: highly uniform vegetation is generally found within annually burned watersheds, upland and lowland terrains are often level enough for sufficient sampling range, and the windy environment encourages turbulent transport. In this study, every effort was exerted to minimize any effect of measurement and processing errors. Additionally, available energy measurements (R_n and G) were positioned within the prevailing footprint of each EC tower to resolve spatial mismatch in the component source areas of the energy budget observations. Nevertheless, energy balance closure was 0.865 and 0.875 at the upland and lowland in 2007, and 0.858 at the upland and 0.936 at the lowland in 2008. Across both years, EC measurements at the watershed-scale accounted for 87.0 and 89.7% of net radiation.

Despite differences between uplands and lowlands, the surface energy budget and degree of closure were not strongly affected by landscape position within the watershed and across years. The largest difference between the two sites was that the lowland had higher λE than the upland by 8% on average.

Only marginal improvement in closure was seen by resolving the scale mismatch that some studies have suggested as a possible reason hindering attempts to close the energy budget with EC (Foken et al., 2006; Kohsiek et al., 2007). The available energy dataset obtained in this study is representative of the EC footprint and is of extremely high quality. There is little indication that any of the R_n and G data had errors on the order of the energy imbalance (i.e., up to 20%).

Sensible heat flux barely varied between sites, and only contributed a small amount to the overall system energy exchange. In 2007, simultaneous data acquisition by a large-aperture scintillometer (LAS) upwind of the upland and lowland towers helped to verify the magnitude of H measurements at each EC tower. No clear evidence shows that any errors exist in EC estimates of H at either site.

When λE is fitted with a correction coefficient, $c_{\lambda E}$ (see section 3.4), near-perfect closure is obtained when λE is increased by a mere 17% ($c_{\lambda E} = 1.17$). Creating a correction coefficient likewise for H yields $c_H = 1.96$, which also results in near-perfect closures when used to compute closure at each site in 2007 and 2008. Considering these corrections, it seems very unrealistic for measurements of H to be off by 96% in order to account for the residual energy in the system. However, it is much more reasonable to posit that an error of approximately 17% could exist between measurement or processing of the λE term.

The energy balance within a tallgrass prairie ecosystem is highly dependent on R_n and λE . Available energy in this environment is largely influenced by the input from R_n (Smith et al., 1992), and for a typical summer in northeast Kansas sensible heat flux tends to contribute less to the total energy output than λE . Given the high degree of confidence in measurements of available energy (particularly R_n) and the lack of evidence pointing to large errors in H, it seems pertinent to take a closer look at possible correlations between λE and the lack of closure within a system. The data presented in this paper do not seem to support the rationale for lack of closure that are often detailed in the literature (i.e., mismatched source areas of available and turbulent energy measurements, overlooked low frequency energy transport, poor instrument quality/calibration or post-processing procedures, nonhomogeneous vegetation within the sampling area, or highly irregular topography). These observations point to a possible systemic

error in λE —given the lack of data suggesting that H is in error—leaving one to ponder if λE is somehow the culprit concerning the overall energy imbalance when using EC. Unfortunately, until the important issue of the energy balance closure problem is fully resolved, researchers are likely to underestimate field-scale evapotranspiration and possibly other scalars (CO_2 fluxes) using eddy covariance.

2.5. References

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Figures and Tables

Figure 2.1. Map of the Konza prairie watershed showing the locations of the upland and lowland EC towers and the LAS beam. Average prevailing wind direction during this study was 175° at the upland (north EC site) and 157° at the lowland (south EC site).

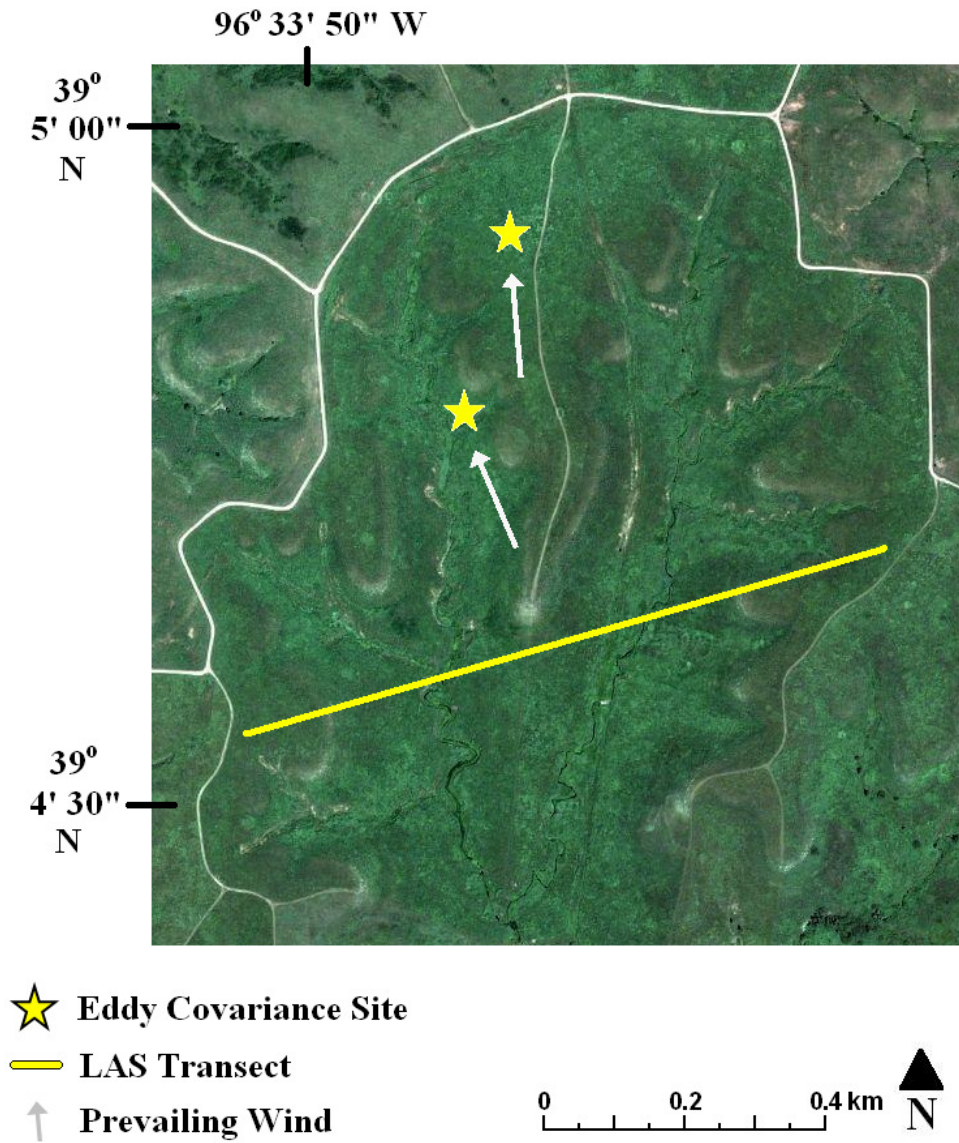


Figure 2.2. Growing season 10-day cumulative precipitation and average volumetric soil moisture at 3.5 cm depth.

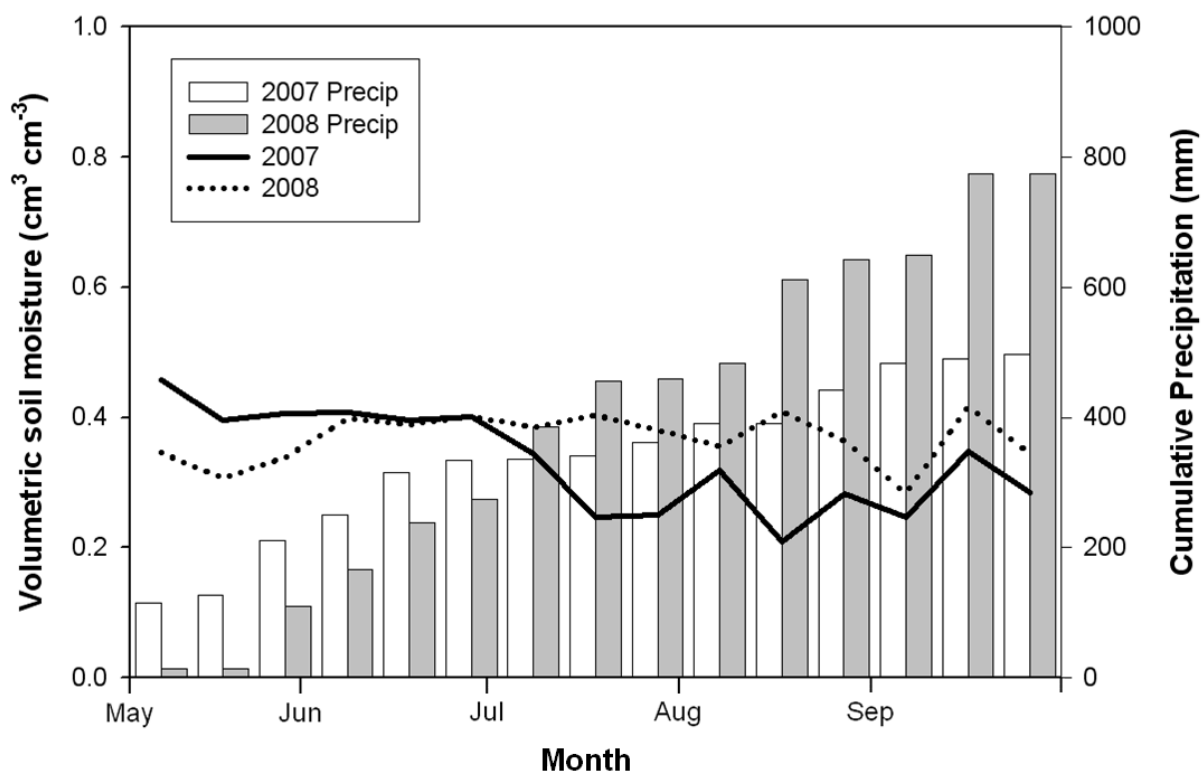


Figure 2.3. Comparison of upland and lowland diurnal energy balance in early and later summer, 2007. All units in W m^{-2} .

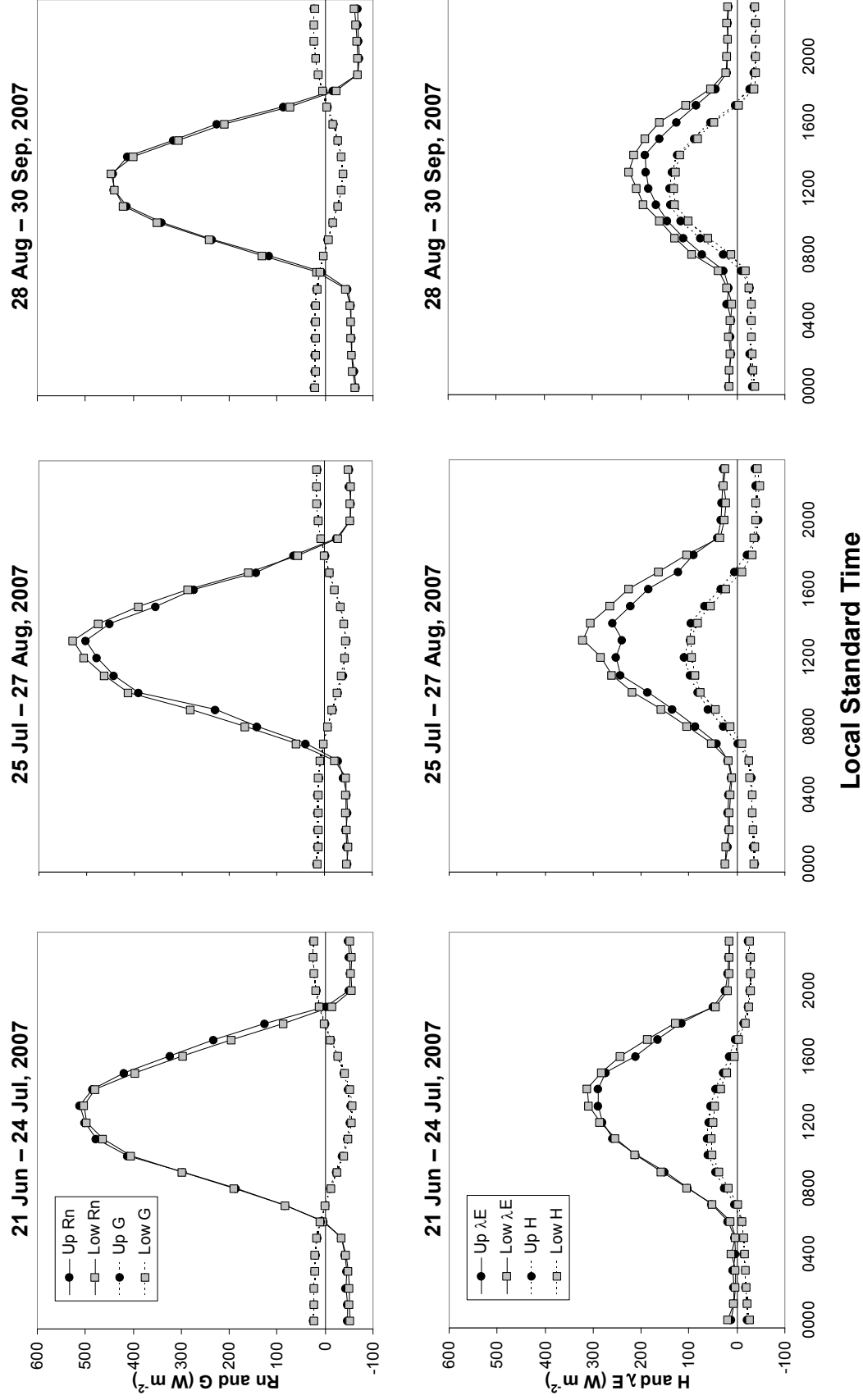


Figure 2.4. Comparison of upland and lowland diurnal energy balance in early and later summer, 2008. All units in W m^{-2} .

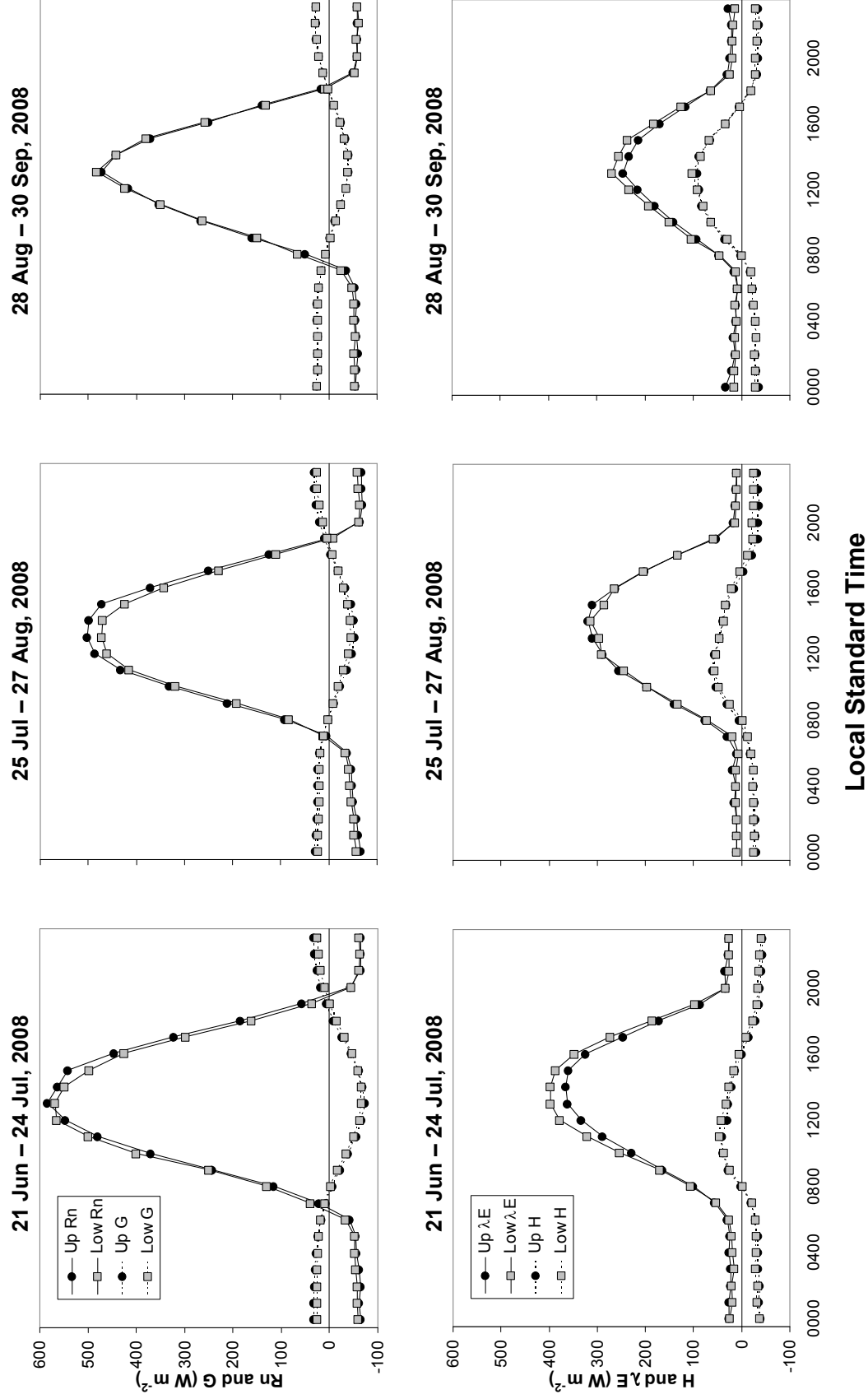


Figure 2.5. Analysis of energy balance closure at the upland and lowland sites during early, mid, and late summer, 2007. All units in W m^{-2} . This graph uses “full filter” data, (i.e. $165^\circ < \theta < 255^\circ$, $u^* > 0.15 \text{ m s}^{-1}$, $R_n > 125 \text{ W m}^{-2}$). Closure was plotted from 30 minute fluxes of H , λE , R_n , and G .

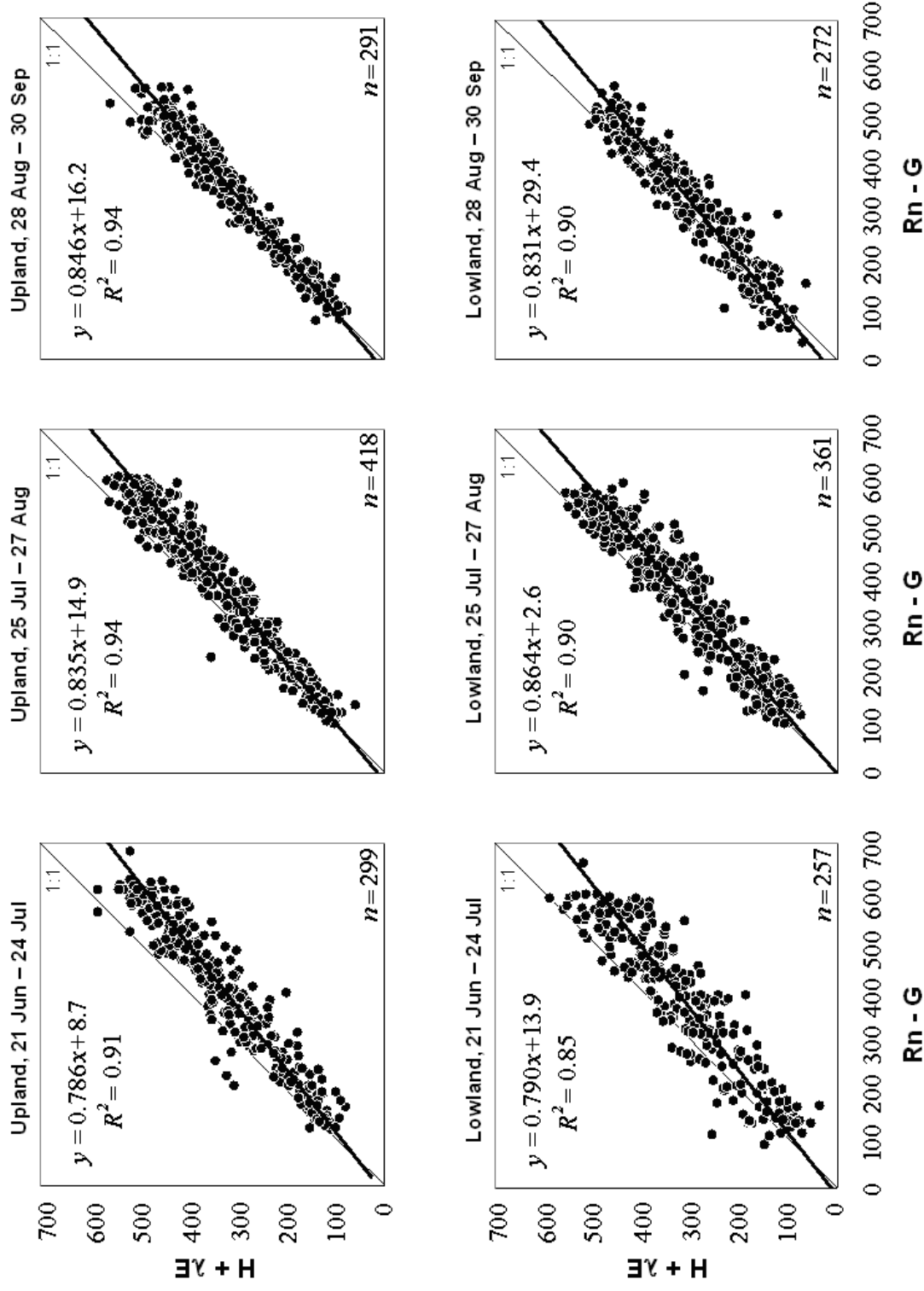


Figure 2.6. Analysis of energy balance closure at the upland and lowland sites during early, mid, and late summer, 2008. All units in W m^{-2} . This graph uses “full filter” data, (i.e. $165^\circ < \theta < 255^\circ$, $u^* > 0.15 \text{ m s}^{-1}$, $R_n > 125 \text{ W m}^{-2}$). Closure was plotted from 30 minute fluxes of H , λE , R_n , and G .

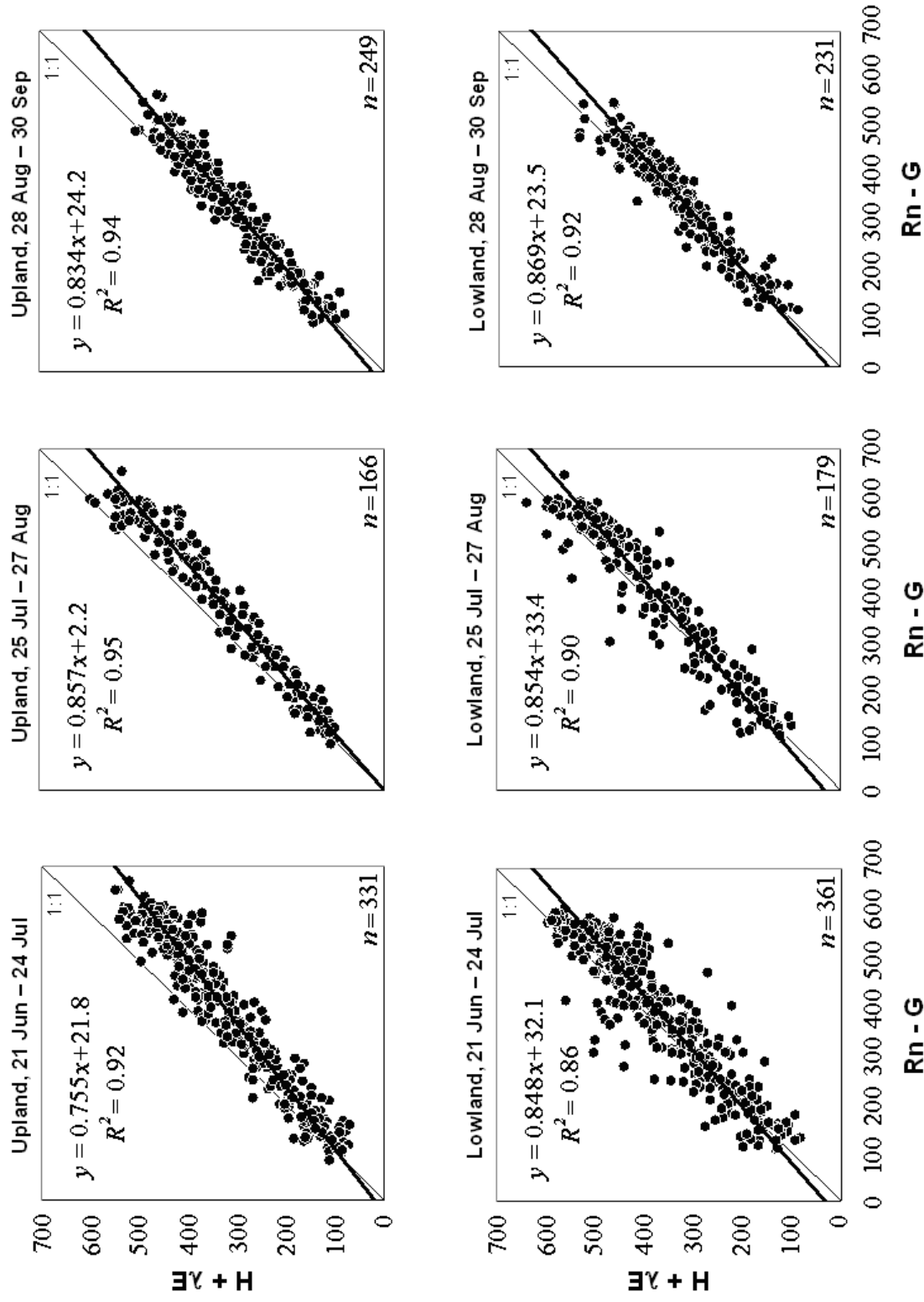


Figure 2.7. Composite of the average diurnal residual energy by local standard time, 21 Jun – 30 Sep 2007 (a) and 2008 (b). (This graph uses data not filtered for wind direction, u^* , or R_n , E_{res} is calculated from eq. 3.)

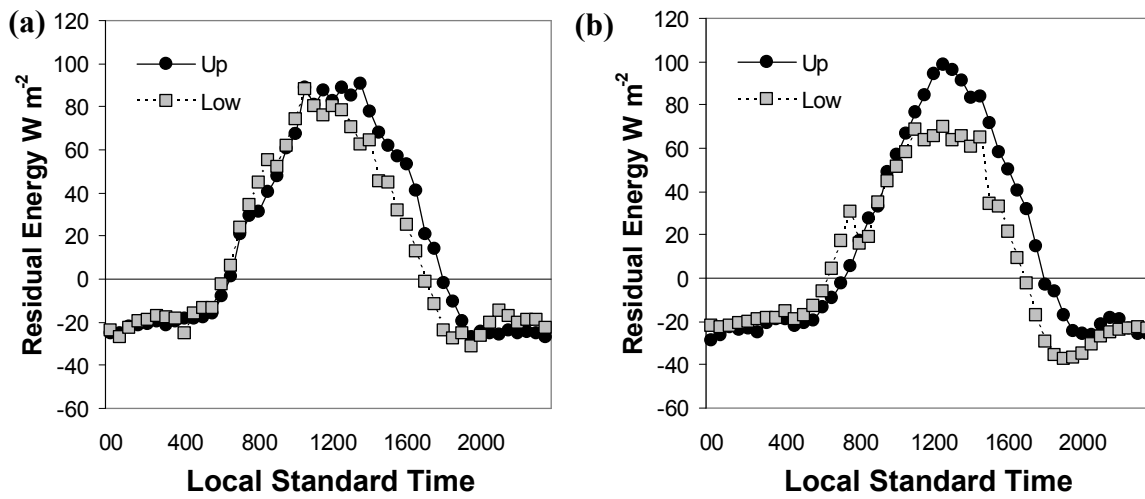


Figure 2.8. Average diurnal difference between G calculated near the EC tower (G_{TOWER}) and in the EC footprint near net radiation measurements ($G_{\text{FOOTPRINT}}$). Data shown are averaged by year. Difference = $G_{\text{TOWER}} - G_{\text{FOOTPRINT}}$

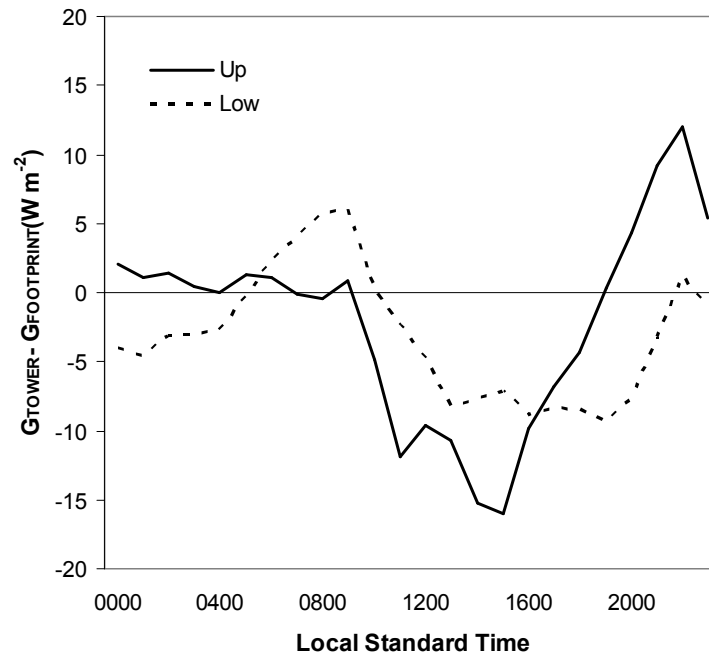


Figure 2.9. Closure as a function of calendar day, 2007 (a) and 2008 (b). Closure was 87.0% (86.5%, upland; 87.5%, lowland) and 89.7% (85.8%, upland; 93.6%, lowland) on average in 2007 and 2008, respectively. (“Full filter” data utilized, i.e. $165^\circ < \theta < 255^\circ$, $u^* > 0.15 \text{ m s}^{-1}$, and daytime where $R_n > 125 \text{ W m}^{-2}$. Closure was computed with eq. 4, where average daily H , λE , R_n , and G were used as input. Data represented are for days that contained at least 3 hours of “full filter” data.)

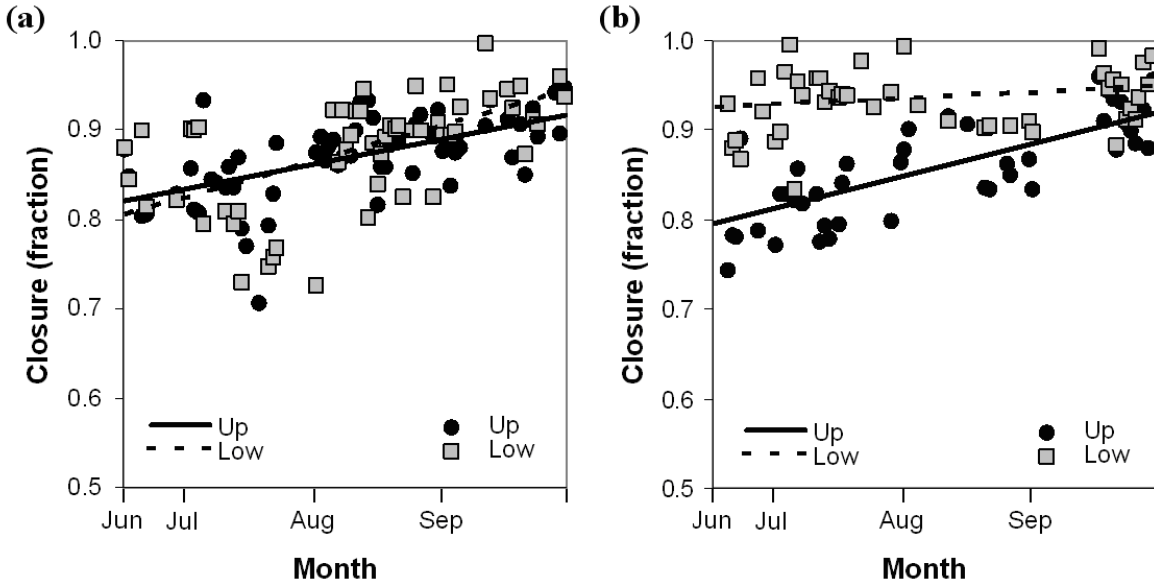


Figure 2.10. Comparison of (a) sensible and (b) latent heat turbulent fluxes measured by the LAS to those from the EC towers, 2007. $\lambda E_{LAS} = R_{n\text{ avg,U\&L}} - H_{LAS} - G_{\text{avg,U\&L}}$ (These graphs use the 30 minute “full filter” data, i.e. $165^\circ < \theta < 255^\circ$, $u^* > 0.15 \text{ m s}^{-1}$, $R_n > 125 \text{ W m}^{-2}$. Data valid for 17 Jul – 4 Sep.)

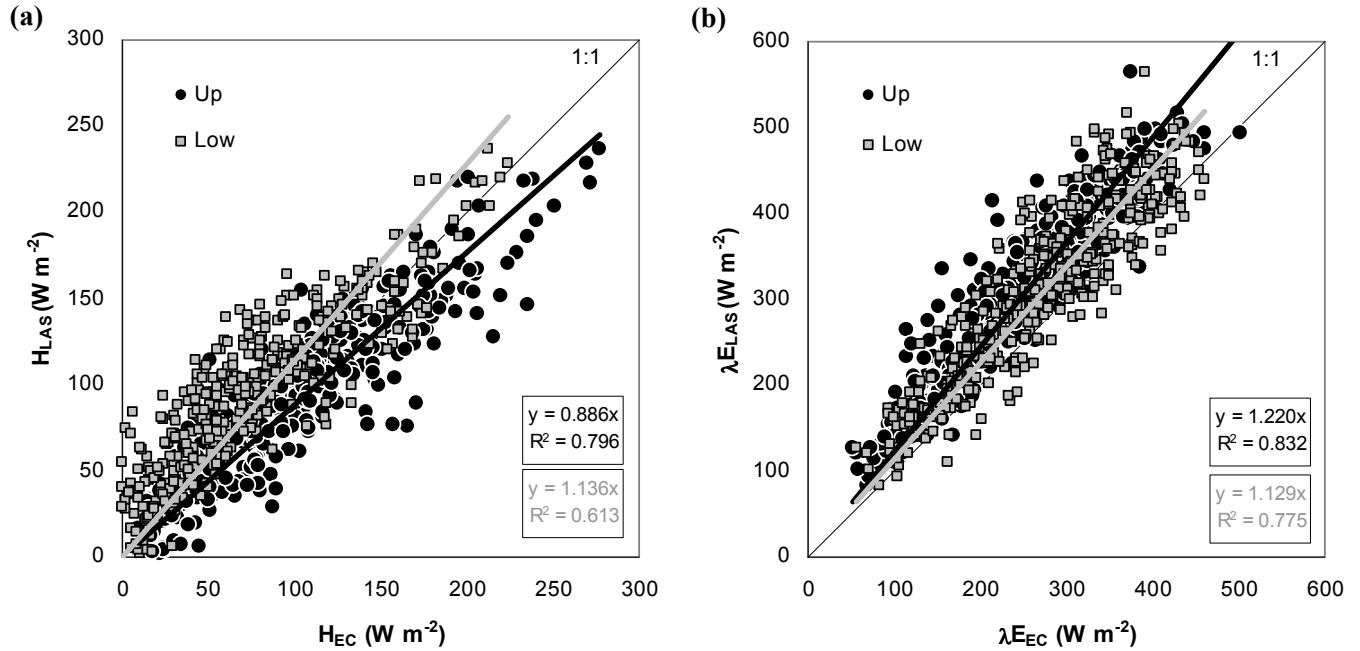


Table 2.1. Green leaf area index and aboveground biomass for each site \pm standard error for the summer 2007, 2008. Leaf area was only measured for 4 of the 8 samples at each location on each date, thus leaf area data may not be as representative of the EC footprint as biomass data.

	Leaf Area Index (cm ² cm ⁻²)		Biomass (g m ⁻²)	
	Upland	Lowland	Upland	Lowland
<i>Date:</i>				
22 May 2007	1.6 \pm 0.3	1.5 \pm 0.3	137 \pm 23	137 \pm 25
24 Jul 2007	3.0 \pm 0.9	3.6 \pm 1.3	482 \pm 65	595 \pm 124
30 May 2008	¹ 1.0 \pm 0.2	¹ 1.5 \pm 0.3	107 \pm 9	147 \pm 52
03 Jul 2008	3.0 \pm 1.2	3.6 \pm 0.7	336 \pm 62	464 \pm 108
21 Aug 2008	2.8 \pm 1.1	3.8 \pm 1.3	539 \pm 117	773 \pm 168

¹ p < 0.065

Table 2.2. Comparison of total evapotranspiration (FAO-56 reference crop ET, average between upland and lowland) and precipitation, all in mm. Data are for DOY 172 – 273.

	Precipitation	ET _o	Precip – ET _o
<i>Date:</i>			
2007	181	459	–278
2008	510	397	113

Table 2.3.

(A) Average daily flux calculated by integrating under the curves in Figs. 2.3 and 2.4 (first four columns for each site). Right column under each site-heading is the average 24-hr cumulative λE -derived ET. Data in Table 2.3a are unfiltered.

<i>Date:</i>	Upland				Lowland			
	λE	H	R_n	G	λE	H	R_n	G
	-----	(MJ m ⁻² d ⁻¹)	-----	-----	-----	(MJ m ⁻² d ⁻¹)	-----	-----
<i>21 Jun – 24 Jul, 2007</i>	9.3	0.5	12.9	-0.6	3.4	0.1	12.2	-0.6
<i>25 Jul – 27 Aug, 2007</i>	10.0	1.3	12.7	-0.6	3.6	0.3	11.7	-0.5
<i>28 Aug – 30 Sep, 2007</i>	6.2	1.7	8.2	0.0	2.4	1.2	8.3	0.0
2007 Average	8.5	1.2	11.3	-0.4	3.1	0.5	10.7	-0.4
<i>21 Jun – 24 Jul, 2008</i>	12.2	-1.1	13.8	-0.8	4.7	-0.8	13.8	-0.9
<i>25 Jul – 27 Aug, 2008</i>	9.8	-0.2	11.3	-0.4	4.0	0.0	10.6	-0.4
<i>28 Aug – 30 Sep, 2008</i>	7.1	0.5	8.0	0.1	2.8	0.6	8.2	0.0
2008 Average	9.7	-0.3	11.0	-0.4	3.8	-0.1	10.9	-0.4

(B) Difference (%) between upland and lowland values for average daytime integrated flux calculated from the full filter data from Figs. 2.5 and 2.6.

<i>Date:</i>	λE	H	R_n	G
	-----	-----	-----	-----
<i>21 Jun – 24 Jul, 2007</i>	-5.8	—	2.2	-3.0
<i>25 Jul – 27 Aug, 2007</i>	-5.3	—	4.3	11.1
<i>28 Aug – 30 Sep, 2007</i>	-13.3	—	-0.3	0.9
2007 Average	-8.1	1	2.1	3.0
<i>21 Jun – 24 Jul, 2008</i>	-9.9	—	2.9	7.5
<i>25 Jul – 27 Aug, 2008</i>	-7.3	—	1.4	5.1
<i>28 Aug – 30 Sep, 2008</i>	-5.9	—	1.8	3.4
2008 Average	-7.7	1	2.1	5.3

% Difference = $(100\%) \times (\text{Flux}_{\text{UP}} - \text{Flux}_{\text{LOW}}) / \text{Flux}_{\text{UP}}$

¹ H data are not presented because daytime integrated H varied near zero and resulted in spurious ratios

Table 2.4. Closure $(H + \lambda E + G)/R_n$. Averages for the three periods, using data from Fig. 2.9.

	Upland	Lowland
<i>Date:</i>		
<i>21 Jun – 24 Jul, 2007</i>	0.816	0.819
<i>25 Jul – 27 Aug, 2007</i>	0.876	0.866
<i>28 Aug – 30 Sep, 2007</i>	0.898	0.927
<i>2007 Average</i>	0.865	0.875
<i>21 Jun – 24 Jul, 2008</i>	0.816	0.928
<i>25 Jul – 27 Aug, 2008</i>	0.864	0.943
<i>28 Aug – 30 Sep, 2008</i>	0.909	0.943
<i>2008 Average</i>	0.858	0.936

CHAPTER 3 - Effect of landscape position and shrub encroachment on carbon and water fluxes in tallgrass prairie

3.1. Introduction

Understanding surface-to-atmosphere transport in the Kansas Flint Hills tallgrass prairie provides a foundation of information vital to many areas of study such as sustainability, the influence of grazing, carbon storage/sequestration dynamics, landscape hydrology, burning effects, and ecological forecasting for assessing the consequences of global climate change on biodiversity (Bremer and Ham, 1999; Bremer, et al., 2001; Briggs and Knapp, 1995; Ham and Knapp, 1998; Heisler and Knapp, 2008; Owensby, et al., 2006; Uys, et al., 2004). Grasslands similar to the tallgrass prairie cover over 40% of the land surface, and 70% of the world's agriculture lies on grasslands (FAO, 2009). Understanding biogeochemical processes from a grassland perspective will improve the analysis of worldwide carbon and water budgets, and will also aid in exploring how to sustain these important biomes. Due to interannual and seasonal variations in weather and ecosystem productivity, a meaningful analysis of surface-atmosphere exchange requires long-term, near-continuous measurement. Eddy covariance (EC) is a measurement technique for obtaining such data because it directly measures fluxes of atmospheric constituents (e.g., carbon dioxide [CO_2], water vapor/latent heat fluxes [λE], etc.) at the watershed/management scale (Baldocchi, 1988). Tower-mounted EC instruments have become the standard for evaluating the carbon storage or release within an ecosystem on an annual basis (Baldocchi, 2003), and are utilized by many continental-scale networks like AmeriFlux, EuroFlux, Fluxnet Canada, OzFlux, AsiaFlux, and the planned National Ecological

Observatory Network (e.g., Aubinet et al., 2000; Baldocchi et al., 2001; Field et al., 2006). It is useful for long-term observations that provide information on how year-to-year variation or land management affects the ability of a particular ecosystem such as tallgrass prairie to become a carbon source or sink. Eddy covariance-derived datasets are helpful for scaling surface observations of carbon dioxide and latent heat flux to regional levels where data are incorporated into ecosystem models (Williams et al., 2009).

Measurements of land-atmosphere exchange in tallgrass prairie were a key element of the First ISLSCP (International Satellite Land Surface Climatology Project) Field Experiment (FIFE) conducted in the late 1980's on the Konza Prairie Biological Station in Kansas (Sellers et al., 1992). During this breakthrough experiment, EC was performed by Verma et al. (1992) to measure carbon and energy fluxes as well as for comparison to other techniques. Since that time, EC has continued to be utilized to assess carbon, water, and energy fluxes in tallgrass prairie (Bremer and Ham, 1999, 2010; Ham and Knapp, 1998; Meyers, 2001; Owensby et al., 2006). Suyker et al. (2003) observed that water availability controls overall grassland production during a growing season. They examined three years of EC data over tallgrass prairie in Oklahoma and found that after considering carbon loss via yearly burning, two of the years displayed carbon neutrality, as relatively little moisture stress was observed throughout the corresponding growing seasons. The remaining of the three years, however, was found to be a carbon source, due mostly to the extreme heat and water stress experienced throughout the most productive portion of the year. They concluded that the severity of moisture stress within the tallgrass environment plays a significant role in determining net carbon exchange (NCE) on an annual basis. Contrastingly, a study performed over tallgrass prairie in Kansas by Bremer and Ham (2010) estimated biannual carbon budgets for two adjacent watersheds (one burned annually, one

biennially) corresponding to two of the three years in the Suyker et al. (2003) study. Bremer and Ham (2010) found greater *biannual* C loss in watersheds burned yearly (389 and 195 g C m⁻² 2 yr⁻¹, annual and biannual burns, respectively). In 1998 – 2000, Owensby et al. (2006) estimated annual NCE in grazed and ungrazed tallgrass pastures in eastern Kansas. Overall, they found that for three burn years, both sites were carbon neutral with the widest range of annual values occurring at the ungrazed site.

While EC allows researchers access to useful field-scale data, applications of EC are primarily performed on upland terrain. Areas such as the Flint Hills possess distinct uplands and lowlands, and no studies have assessed the lowland contribution to carbon, water, and energy balances for the watershed-scale using EC in tallgrass prairie. This is important to study because management decisions are not made for uplands alone, but on a watershed or pasture scale. Several studies have underlined the value of quantifying evapotranspiration (ET) in grasslands (Bremer and Ham, 1999; Bremer, et al., 2001; Ham and Knapp, 1998) which can be measured by eddy covariance, but if lowland ET is not similar to that measured at an upland site, management-scale hydrological estimates could be inaccurate. The same concern is valid for yearly CO₂ budgets (Briggs and Knapp, 1995; Ham and Knapp, 1998).

Not only is topographical position important to consider when compiling yearly carbon and water budgets, but the effect of fire on tallgrass prairie is especially paramount to understanding biogeochemical cycling. Bremer and Ham (1999) detailed that annual burning greatly affects the energy and water fluxes within the first 150 days of the growing season in contrast to an unburned watershed (biannual burn regime) in the same year. Annual burning generally resulted in higher biomass production; however, they stressed the importance of environmental moisture availability, because annually burned sites are more susceptible to water

stress in the early growing season. In addition to topography, many studies have evaluated the impact of woodland encroachment, including *Juniperus virginiana* (eastern red cedar), invasion on tallgrass prairie (Knapp et al., 2008; McKinley and Blair, 2008; Owensby et al., 1973). Briggs et al. (2005) considered the effect of prolonged fire suppression by comparing three watersheds for Kansas tallgrass prairie (burn frequencies of 1-, 4-, and 20-years). For burn intervals of 4 years or greater, woody encroachment becomes the dominant concern. They found that the largest changes occurred in 4-year watersheds where shrubs proliferated at a higher rate than in 20-year watersheds. Briggs et al. (2005) called woody invasion "... a serious threat to the remaining tracts of tallgrass prairie," and stated that dramatic changes in productivity, carbon sequestration, and species diversity will occur with continued conversion to shrublands.

The first objective of this research was to quantify lowland EC measurements of CO₂, water, and energy in comparison to an upland EC site within the same annually burned watershed. Variations in carbon dioxide and λE cycles and balances at the field-scale will be explored and interpreted keeping in mind the inherent differences and similarities between upland and lowland environments in the tallgrass prairie

A second objective in this study was to examine the effect of shrub encroachment utilizing EC measurements located in the lowland of a shrub-infested watershed burned once every four years. Data from the lowland with significant shrub encroachment was contrasted with measurements from the aforementioned annually burned watershed. Both watersheds were ungrazed and boundary-layer fluxes were measured continuously for two years. Data were used to determine the viability of lowland EC measurements, as well as assess the effect of topography and burn regime-induced vegetation changes (i.e., woody shrub expansion) on carbon and water balances.

3.2. Methods and Materials

3.2.1. Site descriptions

Research was performed in pristine tallgrass prairie on the 3487-ha Konza Prairie Biological Station (KPBS), approximately 14 km south of Manhattan, Kansas, USA (39.19 °N, 96.60 °W, 330 m). The landscape of KPBS is partitioned into watersheds that are assigned replicate treatments meant to examine the influence of grazing and burn regime on long-term ecological processes. Data on turbulent fluxes were used from three eddy covariance (EC) stations that operated over two “burn years” each starting in Apr of 2007 and 2008; concluding Apr 2009. Two of the EC stations were within the boundary of an annually springtime burned, ungrazed watershed. The sites were installed at different landscape positions; one on upland terrain (“upland”, 441 m), and one at a lowland position (“lowland”, 427 m) located approximately 350 m south of the upland site (Fig. 3.1). The source area for the upland tower had level, uniform terrain. The lowland site was on a gently sloping footslope near the bottom of the catchment that drained the watershed. Both sites had uniform vegetation dominated by warm-season, perennial C₄ grasses including *Andropogon gerardii* (big bluestem), *A. scoparius* (little bluestem), *Sorghastrum nutans* (indiangrass), and *Panicum virgatum* (switchgrass) (Gibson and Hulbert, 1987). Soils at each EC station are silty clay loams (Benfield series: Fine, mixed, mesic Udic Argiustolls) (Bremer and Ham, 1999). At the upland site, the depth to shale and limestone fragments was approximately 0.6 m, while the lowland site had a deeper surface horizon with no detectable limestone fragments in the top meter. Additional background information on EC in the watershed can be found in Ham and Knapp (1998) and Bremer and Ham (1999, 2010).

The third EC site was deployed in the lowland of a watershed with a 4-year burn frequency (“shrub lowland”, 415 m), positioned 3 km west of the annually burned watershed. The shrub lowland was last burned in 2005 and scheduled to burn again at the conclusion of this study in spring 2009 (KPBS LTER, 2008a). Like the annually burned lowland tower, the EC tower at the shrub lowland site was located near the watershed’s catchment on a footslope. Based on data collected by a KPBS survey throughout the summers of 2007, the dominant species within the lowland of this watershed was the C₄ grass *A. gerardii* (approximately 37% coverage). The most commonly found shrub within the watershed bottom was *Cornus drummondii* (roughleaf dogwood, C₃, 28% coverage), and also to a lesser extent the C₃ shrubs *Rhus glabra* (smooth sumac, 11% coverage) and *Prunus americana* (wild plum, 10% coverage). Many C₃ forb species were widespread throughout the shrub lowland as well: *Aster ericoides* (heath aster, 27% coverage), *Solidago canadensis* (Canadian goldenrod, 23% coverage), *Solidago missouriensis* (Missouri goldenrod, 22% coverage), and the sub-shrub *Amorpha canescens* (leadplant, 19% coverage) (KPBS LTER, 2008b). *C. drummondii* most often occurred in tight groupings, or shrub islands. Approximately 6 – 8 shrub islands occupied the main source area of the EC tower when winds were from the prevailing southerly direction.

Annually burned watersheds showed on average 384 and 581 g m⁻² aboveground net primary productivity (ANPP) for uplands and lowlands with ranges of 161 – 665 g m⁻² and 250 – 980 g m⁻², respectively, over a 16-year study (Heisler and Knapp, 2008). The same study also reports average aboveground biomass to be 444 g m⁻² for lowlands within quadrennially burned watersheds, with a range of 158 – 859 g m⁻². Historical surveys demonstrate that lowland areas possess deeper soils with greater water-holding capacity than uplands, and lowlands within less-frequently burned watersheds exhibit greater soil moisture on average than annually burned-

lowlands (Briggs and Knapp, 1995). The 30-year average annual precipitation for all sites is 859 mm.

3.2.2. Instrumentation and sampling

Identical eddy covariance instrumentation was deployed at all three locations for the measurement of sensible heat (H), latent heat (λE) and CO_2 fluxes (F_c). Instrumentation included an open-path infrared gas analyzer (LI-7500, Licor, Inc., Lincoln, NE), a sonic anemometer (CSAT3, Campbell Scientific, Inc., Logan, UT), and a temperature/relative humidity probe (HMP45C, Campbell Sci.) all mounted 3 m above the surface at each site. Sensor separation between the CSAT3 and the LI-7500 was 0.14 m, CSAT3 orientation was 210° magnetic, and the LI-7500 was rotated 15 degrees vertically towards the footprint to obtain the least obstruction of flow by sensor body on the infrared beam and also to allow water to run off the lens. Eddy covariance data were logged at 20 Hz using a CR1000 data logger (Campbell Sci.) and collected via Compact Flash card at each site. Meteorological data were sampled at 10 s intervals, and averages of these data were computed and logged every 30 minutes. In-situ calibration was performed to zero and span the CO_2 and H_2O measurements from the LI-7500 every two weeks. A LI-610 portable dewpoint generator (Licor, Inc.) was used to span H_2O , and a tank of carbon dioxide of known concentration was used to span CO_2 and zero both CO_2 and H_2O with the additional use of chemical scrubbers.

Meteorological measurements consisted of net radiation and soil heat flux. At the upland and lowland sites on the annually burned watershed, CNR2 net radiometers (Kipp and Zonen, Delft, The Netherlands) were deployed at 2 m near the center of each tower's source area approximately 30 m south of the EC instruments. Soil heat flux was measured using the

combination method (Fuchs and Tanner, 1968; Kimball and Jackson, 1979) at locations 30 m south of the EC tower (near the CNR2 measurements) with a replication installed 3 m south of the tower. Soil instrumentation at each location included: two soil heat flux plates at 7 cm depth (HFT3, Radiation and Energy Balance Systems, Inc., [REBS], Seattle, WA); soil moisture sensors at 3.5 cm (ML2x Theta Probe, Delta-T Devices, Cambridge, UK); and type-E soil thermocouples at 2 and 5 cm (TCAV, Campbell Sci.). Soil heat flux at the surface was approximated as the sum of heat flux at the depth of the plates (7 cm) and the rate change in heat storage in the 0 to 7 cm layer above the plates. Soil heat capacity needed for the heat storage term was computed from soil water content and soil bulk density (1.0 g cm^{-3}) using the equation of deVries (1963). Meteorological data were logged via Campbell Scientific CR23X data loggers and AM16/32 Multiplexers.

Available energy was quantified at the shrub lowland by deploying two sets of R_n and G measurements; one set sampled shrub islands and a second set of sensors were deployed over a shrub-free patch of grass. The measurements at the shrub island and grass site were about 17 m east and 14 m north of the main EC tower, respectively. The available energy sites each contained one net radiometer ($Q^*7.1$, REBS, Inc.) and the same soil instrumentation as that of the annual-burn upland and lowland stations. All sensors were deployed at the same heights as the corresponding measurements within the annually burned watershed, except the soil moisture sensors in the shrub location were inserted at a 45° angle into the soil surface as burying them at depth would be difficult due to shallow roots and heavy root density within the shrub island. In the winter of 2007 – 2008, animals damaged the shrub-site soil moisture sensors, so they were removed from the site and soil moisture measurements from the grass site were used to describe the watershed for the remainder of the study.

Field data for biomass and leaf area index were collected manually at early, peak, and late growth stages at both sites. Each biomass harvest consisted of clipping four 0.25 m² samples each from an east and/or west transect around the main tower footprint (4 – 8 samples total per site). No harvests were conducted within shrub islands, but this should not have a great impact on carbon estimates because the large shrub islands within the EC footprint at the shrub lowland have more resistance to fires and do not lose much vegetation during burns. Dead leaves from shrubs burn during fires, but this also should not have as large of an effect on C losses as the burning of vegetation outside of the shrub islands. Thus, all biomass data from the shrub lowland site are from non-shrub patches, and additionally these data included all detritus from previous years' growth. Samples were taken from a transect east of the main tower at the shrub lowland (a transect west of the tower was logistically difficult to sample and hence omitted from harvesting). Early and peak samples from all EC locations were analyzed for leaf area index and surface density using a LI-3100C Area Meter (Licor, Inc.), and weighed post-drying to obtain biomass estimates representative of the footprint for each main tower.

3.2.3. Data processing

Post-processing of the EC data closely followed the procedures outlined in Baum, et al. (2008). This included utilizing the EdiRe software package (version 1.4.3.1167, R. Clement, University of Edinburgh, UK) to correct EC data for despiking, lag removal, planar fit coordinate rotation (Lee et al., 2004; Wilczak et al., 2001), frequency response corrections (Moore, 1986), sonic-temperature sensible heat flux corrections for humidity (Schotanus et al., 1983), and density corrections on CO₂ and H₂O measurements (Webb et al., 1980). Finalized data were gap filled to obtain annual net carbon and water fluxes (Falge et al., 2001). On an annual basis, the

fraction of gap filled data ranged from 46 to 53% among the three sites. Unsuitable wind directions or inadequate wind speed (i.e., low friction velocity) was the main reason for gap filling.

3.3. Results and Discussion

3.3.1. Environmental conditions and biomass

Annual carbon and water budgets were compiled for two burn years. Within the scope of this study, a burn year commences on the date of the prescribed burn in the annually burned watershed (decided because shrub lowland watershed was not burned before either year in the study period). In both 2007 and 2008 the burn date was 20 Apr (Day of Year, DOY 110). In 2007, growing season precipitation between 1 May and 30 Sep was 496 mm; below the historical average by 21 mm. However, 67% of this rainfall occurred in the first two months, with almost half of the total precipitation occurring in May alone (45%, Fig. 3.2). When this study started, average volumetric soil moisture values at the upland and lowland were at field capacity (around $0.40 \text{ cm}^3 \text{ cm}^{-3}$). During the more heat-stressed portion of the summer in Aug and Sep 2007, two significant drydown periods occurred; DOY 180 to 203 and 216 to 232. The water demand was quite substantial during the latter part of the summer in 2007.

Contrastingly, 2008 was a much wetter year (total precipitation was 747 mm, 230 mm above average for 1 May – 30 Sep). Precipitation events occurred at nearly-even intervals with monthly rainfall totals and soil moisture remaining consistent over the summer. This is atypical behavior because precipitation events tend to be intense and sporadic for this region. Volumetric soil moisture paralleled 2007 data—around $0.40 \text{ cm}^3 \text{ cm}^{-3}$ at each site. In 2008, the environment experienced little stress regarding water supply and heat. This resulted in an exceptionally large biomass production in comparison with 2007 (Table 3.1, section 3.2.1).

3.3.2. Net carbon exchange

A comparison of 30 minute F_c between the upland and lowland annually burn sites are shown in Figure 3.3a. On average, the difference in CO_2 efflux between the two sites was 13.8%; higher at the lowland where more favorable soil water conditions and a larger canopy was present. Even larger differences were observed in comparing the annually burned lowland to the EC measurements of F_c from the shrub lowland (Fig. 3.3b). These both lie near the watershed catchment, and thus, probably share similar deep soils which are conducive to water retention and plant development. However, the larger amount of C_3 vegetation at the shrub lowland (and subsequently, a more sparse distribution of C_4 plants) offset the characteristic one would expect from its location in a low-lying area. Carbon dioxide flux from the shrub lowland was 28% lower than annually burned lowland. This is consistent for both years, despite the large interannual variation in precipitation and ANPP between the two growing seasons. While the fluxes from the shrub lowland before woody expansion are unknown, it is likely that carbon flux per unit land area was diminished when the C_4 warm-season grasses were replaced by woody shrubs. Note: there was no significant change in regression when utilizing only growing season data versus including fluxes from the senescence period as well (e.g., the slope only changed by one-fourth of a percent, data not shown).

Net carbon exchange showed strong seasonal trends across both summers (Fig. 3.4). In the summer of 2007, monthly NCE peaked at 158, 194, and 123 g C m⁻² for the upland, lowland, and shrub lowland, respectively. The same sites showed peak monthly values in 2008 of 167, 187, and 125 g C m⁻², in the same order as 2007 (Fig. 3.4). The shrub lowland both gained and lost carbon at a decreased rate to the carbon cycling that took place in the other watershed.

Throughout both summers, the annually burned lowland displayed greater carbon storage than the annually burned upland and shrub lowland, with peak NCE in June and July. In general, growing season differences between the three sites were less in 2007 (when the system experienced greater water deficits) than in 2008 when moisture was not a limiting factor in ecosystem productivity. In contrast, the largest carbon losses occur during the early period of autumn/winter senescence. Both years in the autumn, temperatures remained mild through Oct and Nov, corresponding with maximal monthly losses of $40 - 58 \text{ g C m}^{-2}$ between all three sites in 2007 and $22 - 38 \text{ g C m}^{-2}$ in 2008, with the highest loss occurring at the annually burned lowland site in 2007 (Oct) and at the upland site for that same watershed in 2008 (Nov). Greater carbon losses occur during these months because there is less carbon storage via photosynthesis and mild autumn temperatures can typically provide an environment that encourages continued soil respiration. Reduced wintertime temperatures slow down root and microbial respiration within the soil resulting in smaller C release in Dec – Feb. Though there is no detectable off-season trend in the differences between the two sites on the annually burned watershed, it is possible that any patterns may have been masked by the greater measurement uncertainty and high fractional gap filling that occurs throughout wintertime senescence.

Net carbon exchange (derived from the data used for Fig. 3.4) is presented as monthly accumulations corresponding to the growing season, senescence, and the entirety of each burn year in Table 3.2a. The largest growing season gains occurred at the upland and lowland sites in the annually burned watershed. Carbon storage was much higher in 2008 than 2007, showing that interannual variability has a large effect on productivity, especially in a C_4 -dominated landscape. From 2007 to 2008, carbon sequestration during the growing season increased by 9, 11 and 8% at the upland, lowland, and shrub lowland sites, respectively. During senescence, the

annually burned upland lost the most carbon (average loss of 160 g C m^{-2} , 35% of growing season gains), with the shrub lowland second (nearly half of summer gains, with an average C loss of 134 g C m^{-2} , i.e., 45%), and the annually burned lowland site lost the least overall (lowest average carbon release of 115 g C m^{-2} , 23% of average summer C gains). Table 3.2a appears to suggest all sites would be net carbon sinks for both years, storing from 159 to $444 \text{ g C m}^{-2} \text{ yr}^{-1}$. However, when the prairie is burned huge carbon losses are incurred, and this needs to be taken into account when determining the overall net carbon exchange.

As indicated, throughout this study the shrub lowland was not as efficient at storing canopy and soil carbon as the annually burned watershed sites. The shrub lowland was not burned before either of the burn seasons this paper covers, the last prescribed burn was conducted in Apr 2005. However, the site was burned at the conclusion of the study, so it was possible to obtain an estimate of annual carbon exchange including the carbon loss due to burning. Because the shrub site had not been burned prior to each burn year, detritus from previous seasons (e.g., the 2005 – 2006 and 2006 – 2007 burn years) had built up over time. Biomass harvests from this watershed near the EC tower demonstrate the accumulation of litter from the beginning of the burn season in 2007 through the end of the second burn year in Apr 2009 (Table 3.1). This litter contributed to the shrub lowland being a net carbon source when it was burned (loss on the order of $336 \text{ g C m}^{-2} \text{ yr}^{-1}$), while the annually burned sites seemed to be carbon sinks, even after biomass loss was considered (Table 3.2b, Fig. 3.5). To obtain a more accurate estimate of carbon losses or gains in less-often burned watersheds, F_c data and ANPP must be measured starting on the date of the burn, and such measurements should last the duration of the burn cycle.

Research regarding burn regime effects on ungrazed prairie was conducted by Bremer and Ham (2010) on the same annually burned watershed as this study, and an adjacent watershed that was burned every two years. Though the two watersheds in their study are much more alike than those presented in this paper, their research showed that the presence of year-old litter reduced net carbon exchange by blocking heat transfer between the atmosphere and the surface, and additionally preventing solar radiation from impinging on new growth.

Previous data in Figs 3.3 and 3.4 showed there were clear differences in NCE among sites. Differences in vegetation (grass vs. shrub) are the main cause of difference among the two lowland sites; however, differences in NCE between the two towers on the annually burned watershed were likely the result of differing plant water relations during cyclic drying periods. A good example can be seen in 2007, when the environment experienced a dramatic change from highly moist conditions in May and June to warmer than normal temperatures and a late-season precipitation deficit (i.e., $ET > \text{precipitation}$). The most notable drydown period occurred between 6 – 16 Aug 2007 (DOY 218 – 228), and as conditions desiccated, differences between the annually burned upland and lowland sites become more evident. Figure 3.6a shows CO_2 fluxes during this period, which initially displays very little difference between both sites. However, as the landscape became more heat stressed photosynthesis at both sites decreased in response to this change, but near DOY 221 the declines become more pronounced in the upland where water was more limiting. A greater decline in ET is observed around DOY 222, where upland EC captures a trend in F_c that is likely midday stomatal closure during the diurnal peak in sensible heat flux (Fig. 3.6a) (e.g., Hamerlynck et al., 1997). This trend is more defined a few days later, at which point vegetation in the lowland demonstrates slight heat stress responses through stomatal closure as well. This protective mechanism was employed by the C_4 grasses at

the upland first and later to a lesser degree in the lowland; water stress is likely delayed or avoided in lowlands during short-term dry periods.

3.3.3. Evapotranspiration and NCE:ET

Upland ET generally traced lowland patterns within the annually burned watershed, underestimating the lowland site consistently by about 20 mm yr⁻¹. Maximums in ET coincided with peak F_c for the annually burned watershed both years, with monthly average daily ET's of 4.7 and 4.9 mm d⁻¹ at the upland and lowland in Jul 2007, and likewise 5.8 and 6.2 mm d⁻¹ in 2008. These findings are consistent with topographical surveys showing greater productivity in annually burned lowlands within the tallgrass prairie (Abrams et al., 1986; Briggs and Knapp, 1995). During the previously-discussed drydown in Aug 2007, λE at the annually burned lowland showed very little deviation in magnitude, while the upland site in the same watershed displayed decreasing λE flux as the precipitation deficit continued (Fig 3.6b). This is a reflection of the conditions in lowlands that contribute to higher ANPP—the abundance of water within the low-lying areas allowed the environment to withstand water and heat stress longer than hilltops.

Despite differences seen during drydowns, overall ET did not vary dramatically between the two sites on the annually burned watershed, however, the lowland shrub site in 2007 had more evaporation, especially in Jun – Aug where environmental demand was high (Fig. 3.7). In 2008, ET was very similar across all sites, which should be expected due to the abundance of moisture and lack of heat stress. Recall that precipitation occurred in nearly-equal intervals (Fig. 3.2), and soil moisture remained fairly stable with no major drydowns. Total measured ET during the first burn year was 720, 740, and 826 mm at the annually burned upland and lowland, and the shrub site, respectively. Overall ET in 2008 was higher at every site, with 763, 783, and

808 mm for the three sites, in said order. At the annually burned watershed, the only month in the 2008 growing season that underestimated ET with respect to the corresponding month in 2007 was May—this month was incredibly wet and accounted for almost half of the total rainfall for the entire summer of 2007.

Higher evaporation was seen at the shrub site due to the water retention within the litter build up, and a greater abundance of C_3 plants, which transpire more than the commensurate amount of C_4 vegetation. These data show that fire frequency is incredibly important for the biogeochemical cycling within a prairie. The shrub lowland that was studied in this paper displayed lower productivity and higher water loss than a lowland site in an annually burned watershed.

A study focusing on the surface energy balance and ET was published by Bremer and Ham (1999) on the same two adjacent burned and unburned watersheds and during the same timeframe as from Bremer and Ham (2010) (see discussion in section 3.2). This research showed that dead biomass from the previous year reduced ET within the unburned watershed as compared to the burned annual watershed. Their data applied to the off-year of a biannually burned watershed, whereas the watershed containing the shrub lowland site discussed in this paper accumulates three times the detritus found on a biannually burned site. Even in a moderately different landscape (e.g., the biannually burned watershed versus a 4-year burn watershed), reducing fire frequency by at least 50% results in noticeable hydrological changes within the landscape. Recent studies have shown that the highest rate of shrub expansion appears to occur within watersheds like the shrub site that are burned every four years (Briggs et al., 2005; Heisler et al, 2003). The contention of these papers is that frequent (e.g., annual) burning kills or suppresses young shrubs, disallowing their ability to develop into a heartier

plant; but infrequent burning on the order of 3 – 4 years allows time for shrubs to grow large enough to withstand fires better. Additionally, developed shrubs tend to prosper after a fire because more resources are widely available and “for the taking” until other species (such as C₄ grasses) reclaim the resource pool.

Due to the encroachment of woody C₃ vegetation, affected watersheds demonstrate lower water-use efficiency. Baldocchi (1994) proposed utilizing the ratio of NCE:ET within an ecosystem as a suitable substitute for water use efficiency. Ratios of NCE:ET (net carbon exchange in g C per kg of water [ET]) are shown in Fig. 3.8, as a negative ratio. References to NCE:ET throughout this paper will refer to the negative ratio, where high NCE:ET displays greater water use efficiency, and a low NCE:ET likewise. By this measure water use efficiency within the shrub watershed was low both years during the growing season, which mirrors our observations of decreased photosynthesis (Fig. 3.4) and increased ET (Fig. 3.7) in contrast to the sites in an annually burned watershed (upland and lowland). Of those sites, the annually burned lowland showed a greater NCE:ET ratio in 2007, but the upland displayed higher ratios for most of the summer from Jul – Sep in 2008. This indicates that during times of environmental stress (like that experienced in 2007) lowlands have an advantage over other terrain locales due to the greater availability of water and nutrients associated with deep soils. Hilltops tend to receive higher winds as well, which dry out the soil sooner than a similar lowland, which is more likely to experience decreased winds resulting from flow distortion around landscape features/hills. As heat and water stress increase, C₄ grasses in the lowland partition their water intake, and transpire less to compensate for decreasing water supplies, thus increasing the NCE:ET of the environment. The trend seems somewhat reversed for part of 2008, where higher NCE:ET occurs at the upland, but the ecosystem was so well watered throughout the growing season, it

seems likely that lowland areas had higher evaporation rates from the soil as a consequence of water retention. Higher soil evaporation combined with plant transpiration (which was probably similar between upland and lowland due to water availability) would create higher levels of ET as measured by the EC tower.

3.4. Conclusions

Because eddy covariance has a large sampling area, it is often assumed that placing a tower within a representative portion of an ecosystem will elicit measurements of good spatial quality. This may be acceptable for many agricultural settings, but in the Flint Hills, it is an assumption that should not go unchecked. The tallgrass prairie biome that occupies a significant portion of the Kansas/Oklahoma Flint Hills consists of undulating terrain with elevation differences between uplands and lowlands from 10 to 20 m or more. Large amounts of runoff are likely due to the intense thunderstorms that pass through the prairie domain, and this runoff carries with it soil and nutrients that are deposited in low-lying areas within a watershed. Deeper soils within lowlands entail greater water-holding capacity, enabling these areas to avoid water or heat stress longer than uplands or hillsides; all these factors support the contention that lowlands possess higher biomass production/ANPP (Briggs and Knapp, 1995; Heisler and Knapp, 2008) (Table 3.1).

Not only is it important to quantify topographical differences when considering carbon and water balances within the tallgrass ecosystem, but it is also crucial to assess the impact of shrub encroachment on native prairie. This problem is seen as the largest threat to last remnants of tallgrass prairie (Briggs and Knapp, 1995; Briggs et al., 2005; Heisler et al., 2003; Heisler and Knapp, 2008). Changes in species diversity within the prairie are likely to have a long-lasting effect on energy, water, and carbon fluxes within this environment.

In this study, we first analyzed the effect of topographic position within an annually burned (i.e., homogeneous), ungrazed watershed (section 3.2). For the two different locations, lowland λE was greater than upland λE by 7% due to higher evapotranspiration near the

catchment (data not shown). The lowland site also showed elevated CO₂ fluxes over those measured by upland EC by 13.8% on average (Fig. 3.3a). Data from the lowland site showed that plant photosynthesis responded more quickly to water shortages than evaporation (Fig. 3.5), supporting research by Suyker et al. (2003). Variation in fluxes between topographical positions were minimized during wet periods because the factors that typically limit productivity (e.g., vapor pressure deficit or an excessively warm environment) are less pronounced. This was also true for ET on the shrub lowland compared to the annually burned lowland when both watersheds were well-watered (Fig. 3.7).

Carbon dioxide fluxes at the shrub site were 72% of those at the annually burned lowland (Fig. 3.3b). Estimates of net carbon exchange show the shrub site to be a carbon sink in 2007 – 2008 (Table 3.2a), however, carbon losses from burning did not occur in this watershed during the spring burn season in Apr 2008. The shrub lowland watershed was burned in Apr 2009, and the loss of carbon showed this site to be a carbon source. When carbon losses were considered at the annually burned sites, both upland and lowland appeared to be carbon sinks each burn year (Table 3.2b).

Water use efficiency, represented by the ratio of NCE:ET, provides a good visual of carbon and water relations throughout the growing season. Analysis of NCE:ET showed that the annually burned lowland site tended to have the highest ratio (that is, the least amount of water loss to concomitant gains in carbon), but in 2008 when the ecosystem was well-watered, soil evaporation at the lowland may have contributed to higher water loss in Jul – Sep 2008 where the upland displayed greater NCE:ET (Fig. 3.8).

An important concept to keep in mind is this intrinsic dependence the tallgrass prairie has on fire. Species diversity, NCE, surface hydrology, productivity, and sustainability are all

affected by the frequency (or infrequency) of applied fires. Burning is an incredibly vital component of the ecosystem carbon balance, and must be accounted for and quantified carefully. For a carbon budget to accurately represent watershed-scale exchange, the timeframe of data collection must match burn frequency and coincide with prescribed burns (e.g., 4 years of data starting on the date that a 4-year watershed is burnt). In addition to fire, considering the contribution of lowlands to overall carbon, water, and energy budgets will assist the exploration of the various topics touched upon in this study. These data help to build a good base for ecosystem model verification and development.

3.5. References

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Figures and Tables

Figure 3.1. Satellite imagery of the woody watershed with visible shrub islands (on left), and the annually burned watershed on right. The location of eddy covariance stations are marked with stars. Source: Google maps

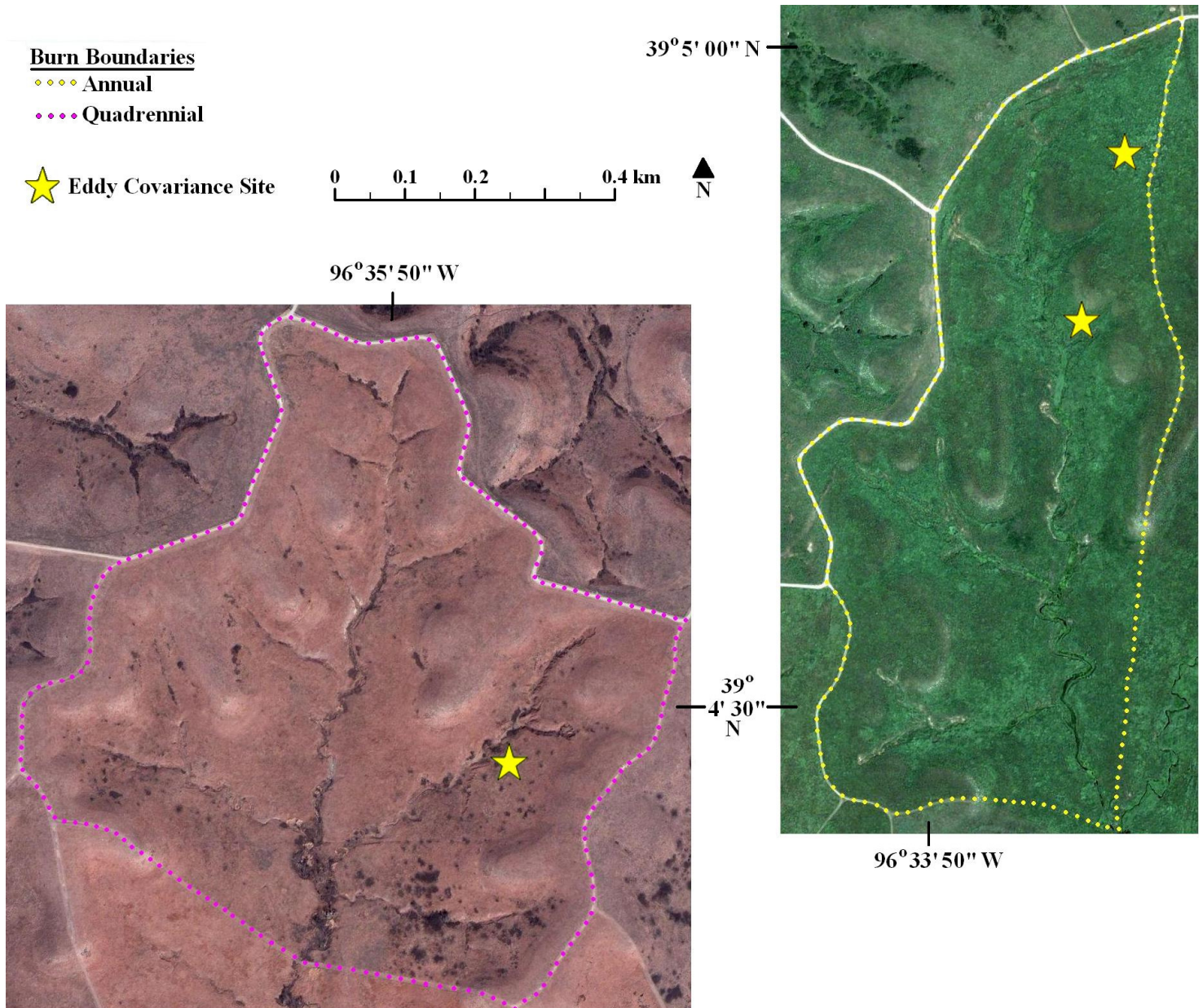


Figure 3.2. Annual cumulative precipitation (vertical bars) at the upland and shrub lowland sites, and 10-day averages of volumetric soil moisture at 3.5 cm depth (lines) for all three EC sites.

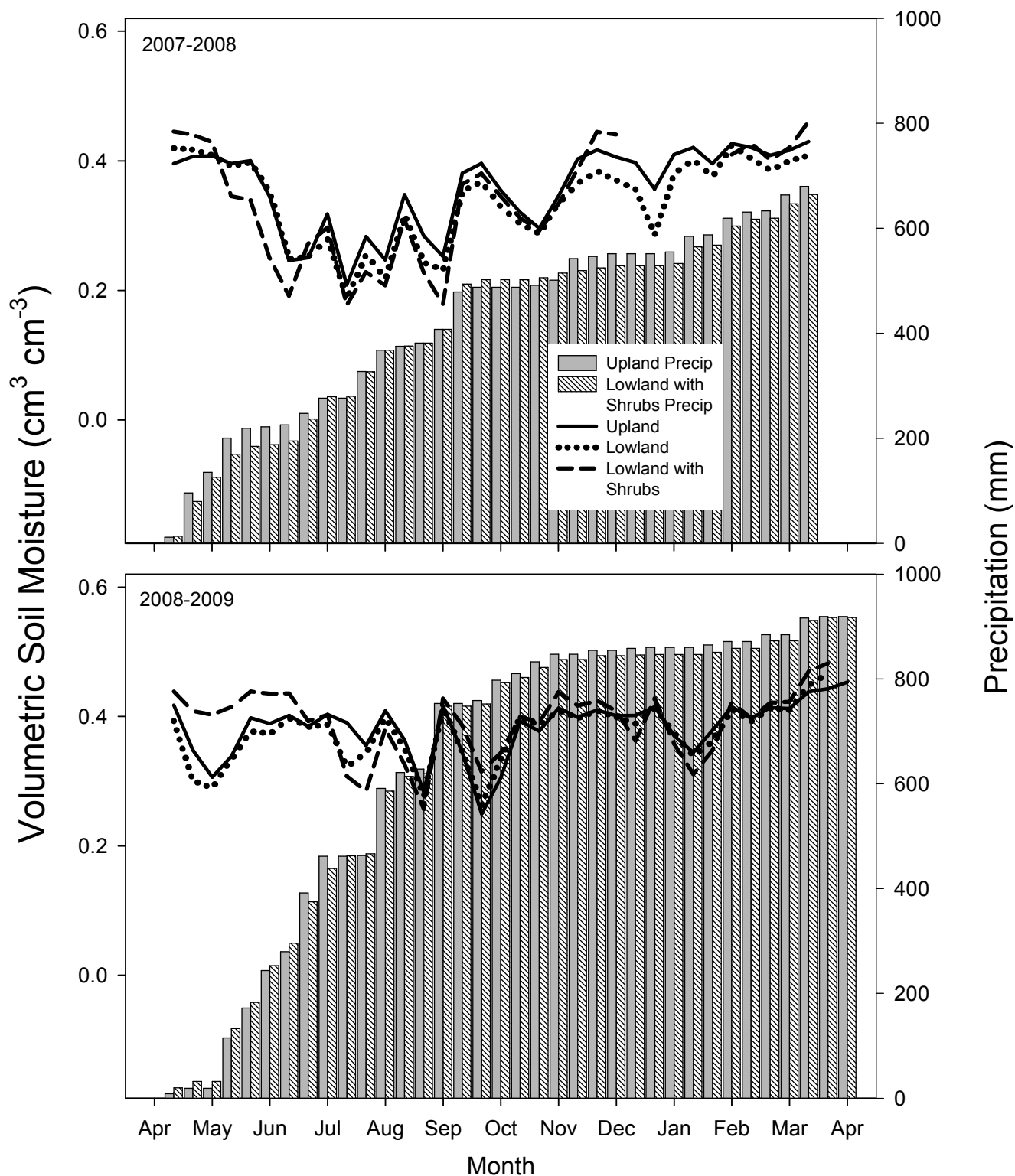


Figure 3.3. Comparison plots of CO₂ flux between (a) the lowland and upland annually burned sites and (b) the annually burned lowland and shrub lowland. Dashed line shows 1:1 ratio.

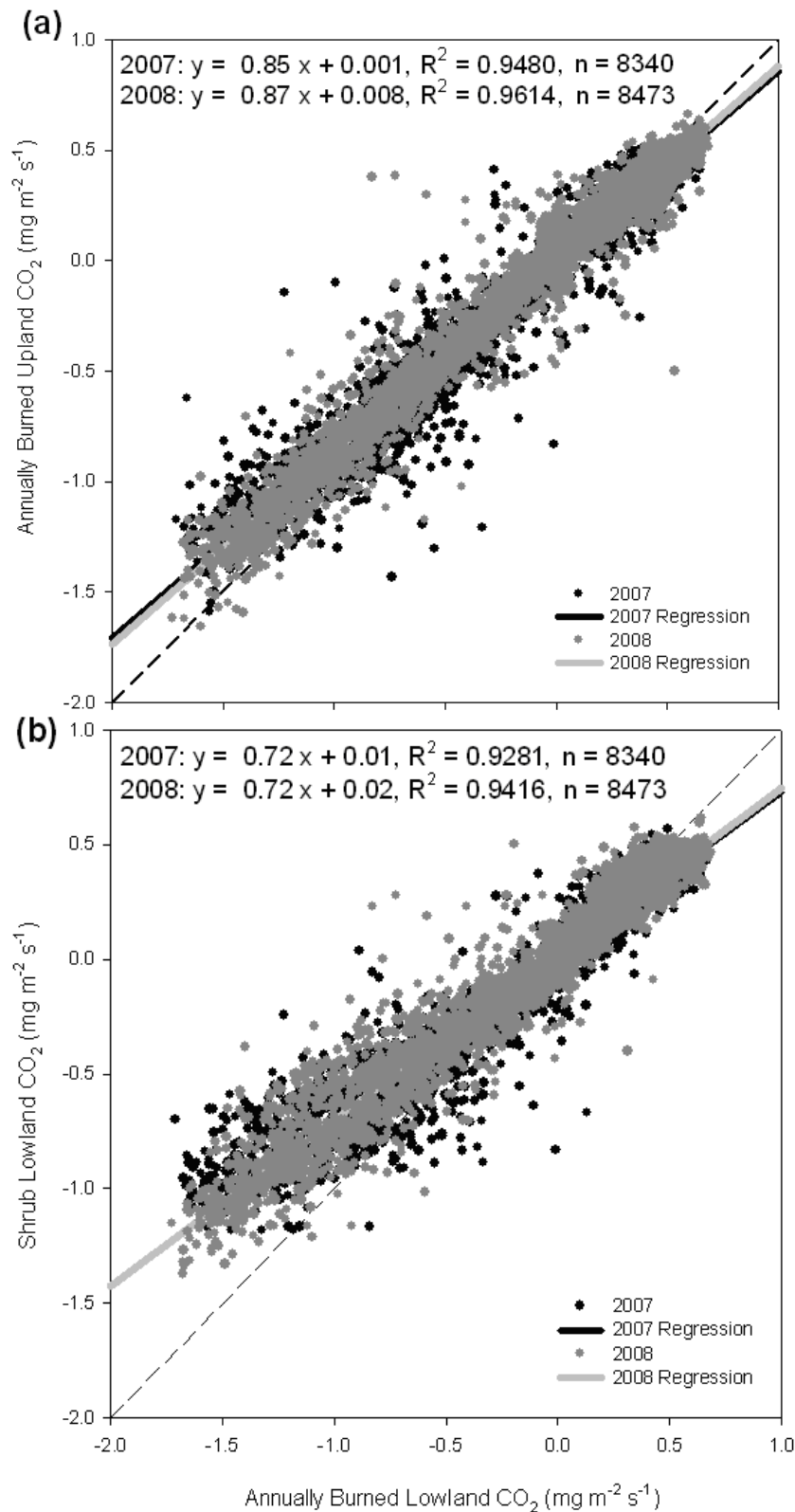


Figure 3.4. Monthly net carbon exchange at the three EC sites, across two burn years. Positive numbers indicate C loss and negative numbers are C gains.

*Apr 2009 was not a complete dataset (04/01/2009 – 04/08/2009)

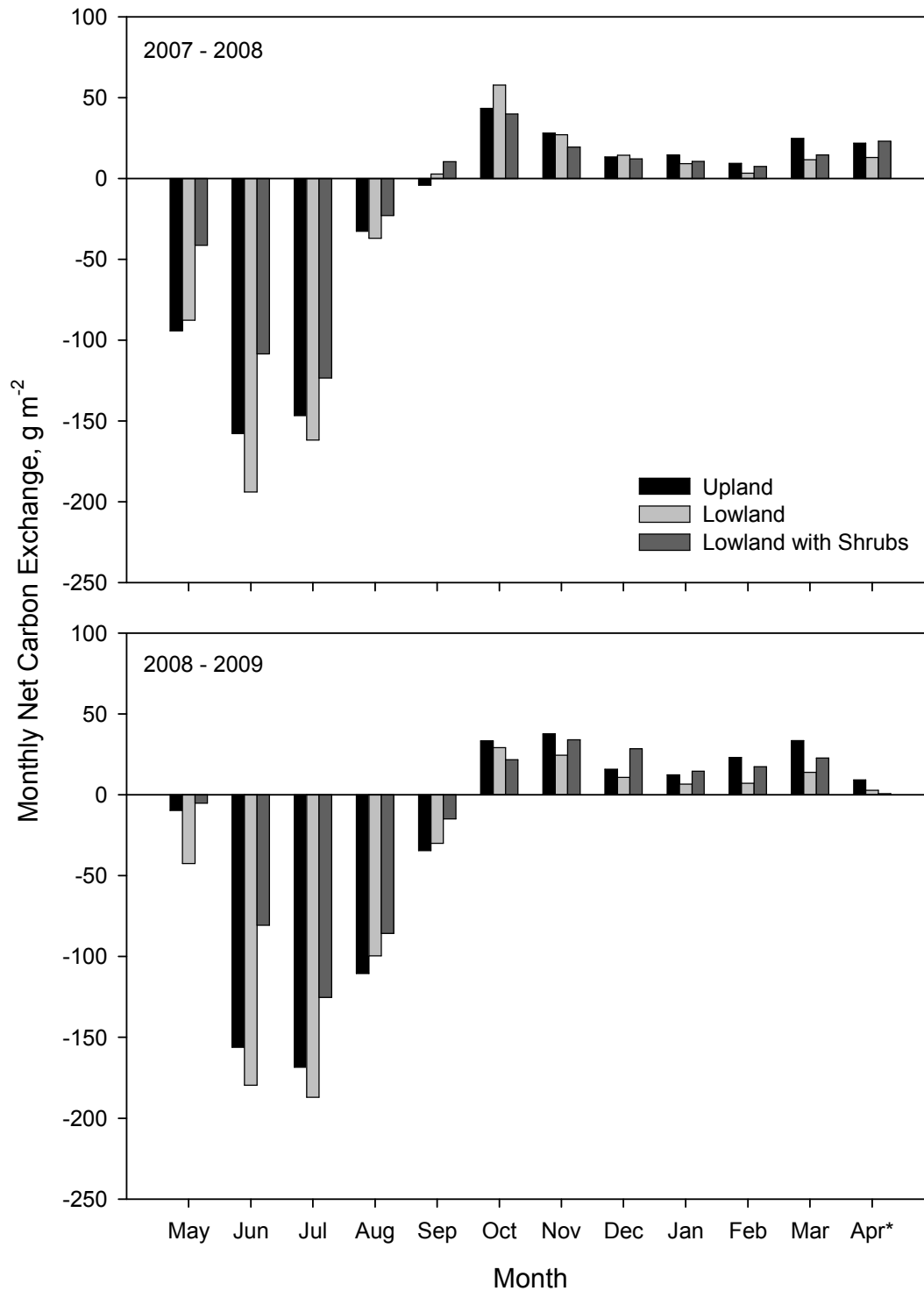


Figure 3.5. Annual carbon balance for the first burn year of the study (i.e., spring 2007 – spring 2008), and the second burn year (spring 2008 – spring 2009).

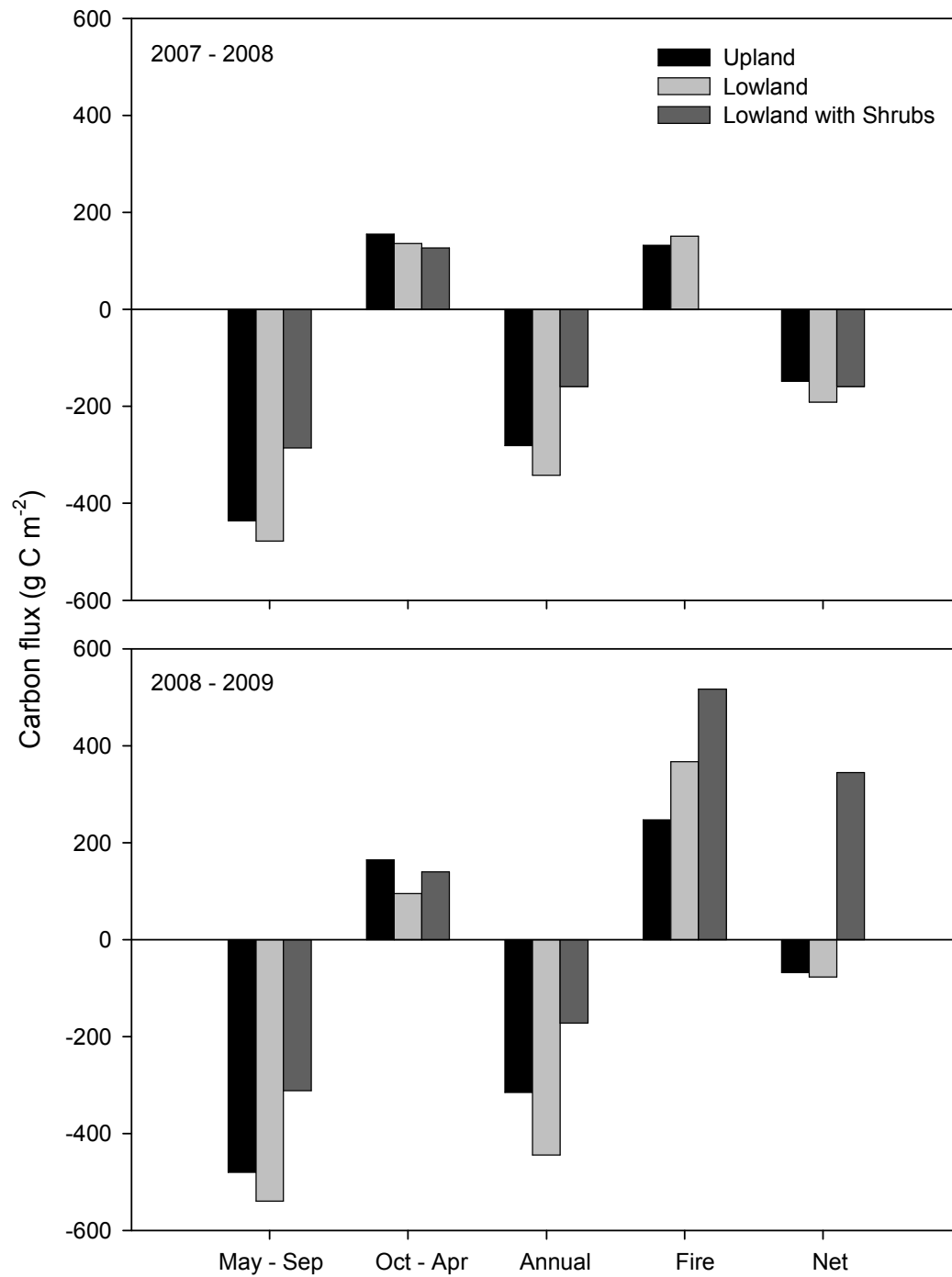


Figure 3.6. Comparison of carbon and water vapor fluxes at the upland and lowland sites on annually burned prairie for 6 – 16 Aug 2007 during a major drydown (a) CO₂ flux, and (b) λE flux.

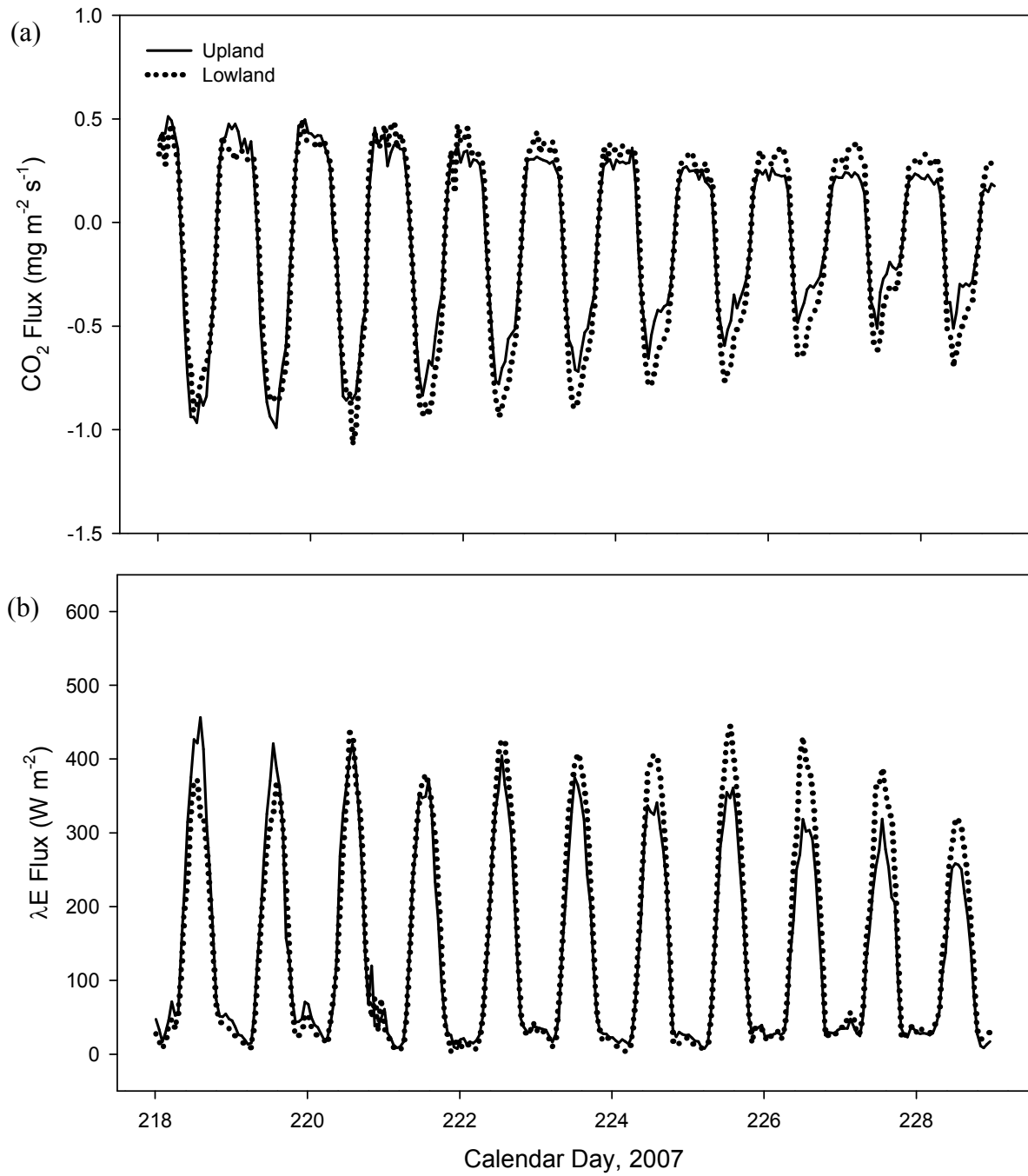


Figure 3.7. Cumulative monthly evapotranspiration (ET) at each site for two burns years.
 *Apr 2009 was not a complete dataset (04/01/2009 – 04/08/2009)

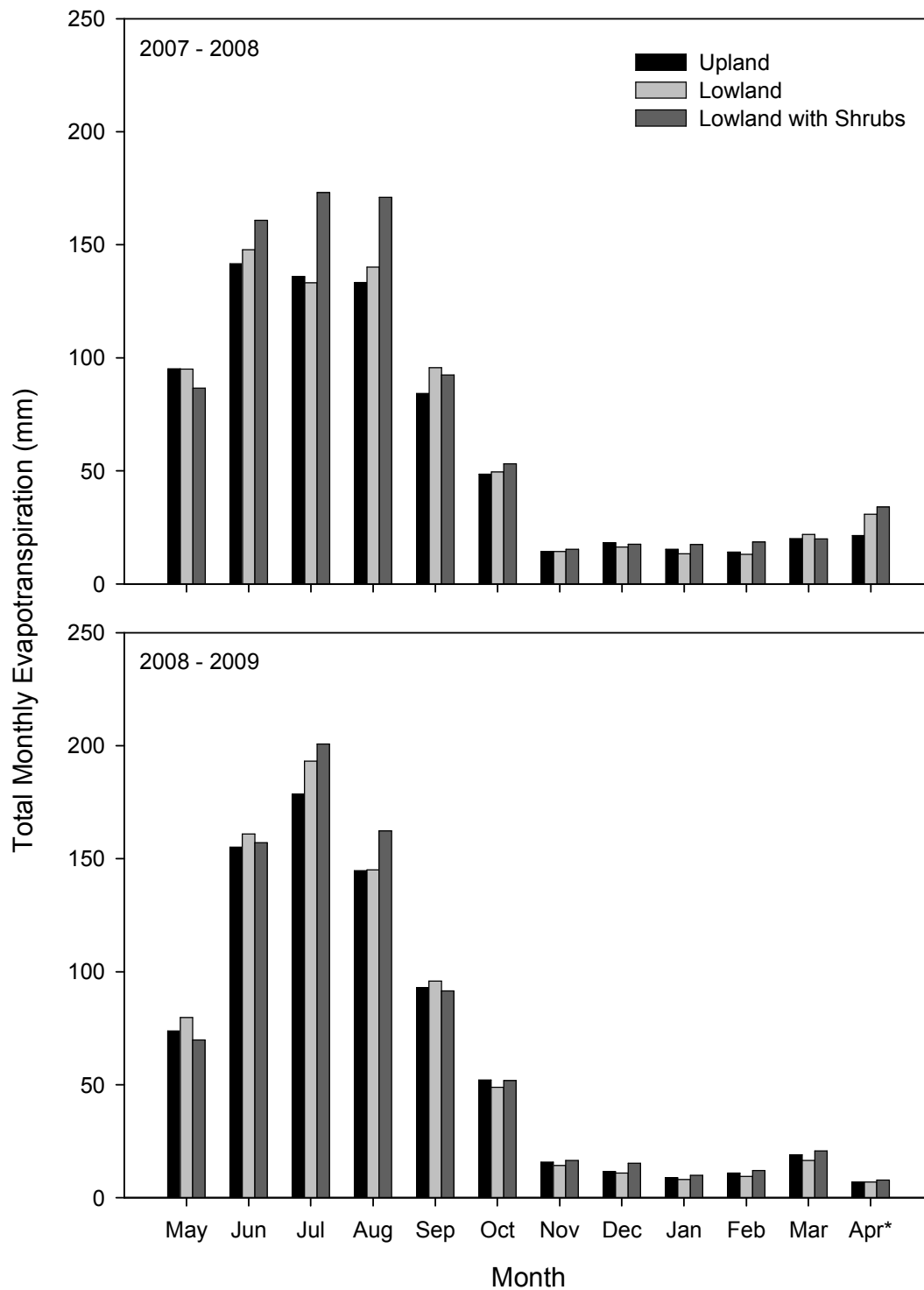


Figure 3.8. Ratio of NCE to ET as a surrogate for water use efficiency for summer 2007 and 2008. Note that the ratio is negative, hence positive ratios show greater photosynthesis occurred with less water loss (indicative of C₄ plants) versus lower ratios that exhibit lower photosynthetic activity but greater moisture losses.

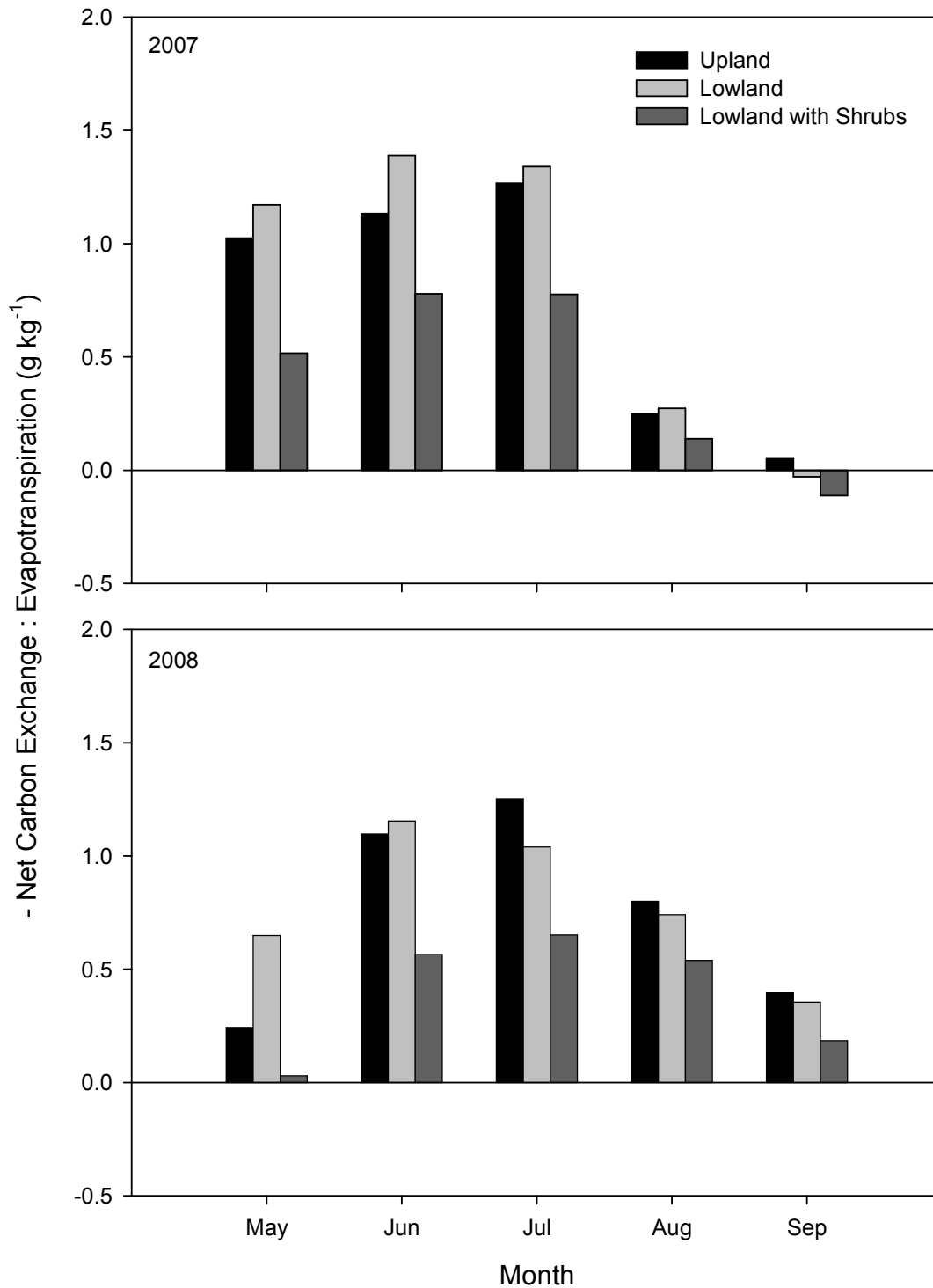


Table 3.1. Green leaf area index and aboveground biomass (ANPP) for each site \pm standard error for the burn years 2007 – 2008 and 2008 – 2009. Biomass estimates at the shrub lowland include litter and standing dead.

Note: Losses of ANPP during winter are often due to increased decomposition as a result of prolonged periods of snow buildup, and current research in this area indicates typical wintertime losses to be about 10% (personal communication, Jay Ham, Colorado State University, Ft. Collins, CO). Greater snow cover in the winter of 2007 – 2008 probably caused a greater percentage loss of ANPP than the winter of 2008 – 2009. Also, increases in biomass reported in this table from 21 Aug 2008 to Apr 2009 are due to continued growth throughout the autumn in 2008 (well-watered conditions in the summer of 2008 caused a delay in senescence). It is likely that losses were incurred throughout the winter, but this does not show up in the data because we did not obtain a true *peak* biomass estimate during the 2008 growing season.

	Leaf Area Index (cm ² cm ⁻²)			Biomass (g m ⁻²)		
	Upland, 1-yr	Lowland, 1-yr	Lowland Shrub, 4-yr	Upland, 1-yr	Lowland, 1-yr	Lowland Shrub, 4-yr
<i>Date:</i>						
22 May 2007	1.6 \pm 0.3	1.5 \pm 0.3	1.1 \pm 0.4	137 \pm 23	137 \pm 25	628 \pm 86
24 Jul 2007	3.0 \pm 0.9	3.6 \pm 1.3	2.3 \pm 0.5	482 \pm 65	595 \pm 124	1046 \pm 136
Apr 2008	¹ —	¹ —	¹ —	308 \pm 72	351 \pm 107	867 \pm 306
30 May 2008	³ 1.0 \pm 0.2	³ 1.5 \pm 0.3	0.7 \pm 0.1	107 \pm 9	147 \pm 52	291 \pm 69
03 Jul 2008	3.0 \pm 1.2	3.6 \pm 0.7	3.5 \pm 0.8	336 \pm 62	464 \pm 108	976 \pm 191
21 Aug 2008	2.8 \pm 1.1	3.8 \pm 1.3	2.3 \pm 0.4	539 \pm 117	773 \pm 168	1088 \pm 118
Apr 2009	¹ —	¹ —	¹ —	575 \pm 158	854 \pm 26	² 1182

¹ Leaf area index analysis was not performed on biomass clippings just before the burn.

² A preburn biomass sample was not obtained at this site in Apr 2009. This number is estimated by obtaining a multiplier for the 2008 late-summer biomass samples at the shrub lowland to predict wintertime change in aboveground biomass. The multiplier was determined by checking the ratio of late-summer to preburn biomass amounts at the annually burned upland and lowland sites. Upland multiplier = 1.07, lowland multiplier = 1.10. Because the shrub EC site is in a lowland, the multiplier of 1.10 was applied to the shrub lowland. (E.g., annually burned lowland 2008-09 mult = 854 / 773 = 1.10; new shrub lowland biomass Apr 2009 = 1088 * 1.10 = 1182)

³ p < 0.065

Table 3.2. Total carbon gains and losses by site, season, and burn year.

(A) Cumulative NCE for each burn year. Growing season NCE are positive fluxes (towards the ground) between late Apr and Sep. Senescence NCE are negative fluxes during the winter, Oct – early Apr. All units are in g C m^{-2} .

	Site	Annual NCE g C m^{-2}	Growing season NCE g C m^{-2}	Senescence NCE g C m^{-2}
<i>Burn year:</i>				
5/7/07 – 4/20/08	Upland	281	436	–155
	Lowland	342	478	–136
	Shrub Lowland	159	286	–127
4/21/08 – 4/24/09	Upland	315	480	–165
	Lowland	444	539	–95
	Shrub Lowland	172	312	–140

(B) Annual NCE after considering the carbon loss during the prescribed burns. Using the framework of Suyker et al. (2003), an uncertainty in pre-burn annual NCE of 25% was used (from Goulden et al., [1996]). Ranges for total NCE were computed using the ³error propagation rule for addition and subtraction. Carbon loss is found by collecting aboveground biomass prior to the burn and multiplying it by the C content of ANPP (43%, determined from watershed samples by Kansas State Univ. Soil Testing Lab).

	Site	Pre-burn annual NCE (see Table 3.2a) (with 25% uncertainty: $\sigma_{\text{PREBURN NCE}}$) $\text{g C m}^{-2} \text{ yr}^{-1}$	Carbon lost to burn (with standard error: $\sigma_{\text{BURN LOSS}}$) $\text{g C m}^{-2} \text{ yr}^{-1}$	Total NCE including burn losses (with uncertainty: $\sigma_{\text{TOTAL NCE}}$) $\text{g C m}^{-2} \text{ yr}^{-1}$
<i>Burn year:</i>				
5/7/07 – 4/20/08	Upland	281 ± 70	-132 ± 31	149 ± 77
	Lowland	342 ± 86	-151 ± 46	191 ± 98
	Shrub Lowland	159 ± 40	—	¹ 159 ± 40
4/21/08 – 4/24/09	Upland	315 ± 79	-247 ± 68	68 ± 104
	Lowland	444 ± 111	-367 ± 11	77 ± 111
	Shrub Lowland	172 ± 43	² -508	-336

¹ This is equal to the annual NCE at the shrub lowland because this site was not burned in 2008.

² A preburn biomass sample was not obtained at this site in Apr 2009. This number is estimated by obtaining a multiplier for the 2008 late-summer biomass samples at the shrub lowland to predict wintertime change in biomass. Multiplier was determined by checking the ratio of late-summer:preburn biomass amounts at the annually burned upland and lowland sites. Upland multiplier = 1.07, lowland multiplier = 1.10. Because the shrub EC site is in a lowland, the multiplier of 1.10 was applied to the previous sample from late summer 2008, after which the carbon content within the biomass was calculated for the above graphs.

³ From Scarborough (1966): $\sigma_{\text{TOTAL NCE}} = ((\sigma_{\text{PREBURN NCE}})^2 + (\sigma_{\text{BURN LOSS}})^2)^{0.5}$

CHAPTER 4 - Conclusion

This research utilized eddy covariance to examine the effect of topography and burn regime on annual carbon and water budgets, while additionally performing an intensive assessment of “the energy balance closure problem” in the Flint Hills of Kansas.

Data from the energy balance (EB) closure study provide evidence that many of the well-cited reasons for lack of closure do not contribute to the overall energy imbalance for EC measurements in tallgrass prairie. First, post-processing procedures were applied to data utilizing commonly agreed-upon methods within the micrometeorological community. The EC sites were well-maintained, and Ogive analyses precluded low frequency flux contributions from the ecosystem. Also, R_n and G measurements were aligned with the main EC source area. This configuration addresses arguments that surface inhomogeneities between $R_n - G$ and $H + \lambda E$ source areas hinders closure. Based on recent literature and data analysis, there is little reason to suppose errors from $R_n - G$ account for the “missing” energy. Topography (upland versus lowland) slightly influenced closure, but seemed mostly connected to λE which comprises more of the outgoing EB component in lowlands, correlating with higher closures there. Deployment of a large-aperture scintillometer (LAS, a measure of watershed-integrated H) within the study watershed gives good agreement in H between LAS and EC (given scale and technique differences). There is no confounding evidence suggesting EC estimates of H are inaccurate. From this λE was briefly investigated, and we found that correcting λE by only 17% results in near-perfect closure. Data suggest possible issues in measurement or processing of λE , and further research should be conducted to assess the accuracy of λE measurements by EC. An error in the EC-derived λE term would impact global CO_2 estimates.

Topographical position was again considered to examine carbon and water budgets and fire effects on woody invasion. Results show 14% higher C storage at lowlands than uplands in annually burned watersheds, and 28% higher in annually burned lowlands than lowlands with shrub encroachment. Contrastingly, lower burn frequency results in higher ET within the shrub watershed, while the annually burned lowland had greater ET than a neighboring upland. Utilizing the ratio of NCE:ET on a monthly basis provides a surrogate for water-use efficiency. This ratio showed that annually burned lowlands react better to heat and water stress. Shrub lowland NCE:ET is about 50% less than either annually burned site, reflecting greater C₃ species abundance (which are typically less efficient at photosynthesis) within the shrub watershed. The three sites had less variation in ET and NCE:ET in well-watered conditions. All sites appear to be C sinks initially, but C losses from the prescribed burns must be considered. Doing so results in annually burned sites functioning as slight carbon sinks, while the shrub site was a carbon sink the year it was not burned, and the second year burning created a carbon loss large enough for this site to be a C source. Continuation of this research should involve measurements at the shrub site for the duration of a burn cycle to assess complete carbon budgeting within the watershed. Models of upland versus lowland terrain could also be adapted from this dataset, so that the lowland component won't be overlooked in an environment like the tallgrass prairie where significant differences can occur between hilltops and footslopes.

Surface-atmosphere exchanges of scalars and energy are highly dependent on the source region, where small changes in land management practices can lead to large changes in surface hydrology, carbon budget, productivity or sustainability within an environment. Compiling annual C and ET balances is often done using eddy covariance, which has to prove an accurate method for such data to have the greatest benefit.